Advances in RF SAW Substrates

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Abstract - In the last decade, surprising advances have been made in the performance of SAW RF filters. The decrease in insertion loss is an excellent example. Today, the typical insertion loss for SAW RF filters for handset is often 2 dB. Advances in RF filter performance continue. Soon RF SAW filters with less than 2 dB typical insertion loss will become common place. This paper gives a review of the recent and some current advances made in SAW RF filter substrates to further improve the performance of SAW RF filters, particularly in insertion loss. These advances include 1- reduction in BAW leakage of the propagating LSAW, 2- increase in coupling coefficient (Ksq), 3- reduction of the temperature coefficient of frequency (TCF).

I Introduction

The demands of the global cellular phone market have inspired impressive advances in cellular phone technologies. Approximately 15 years ago, these demands resulted in the introduction and wide acceptance of SAW RF filters into cellular handsets. Since that time many impressive advances have been made in SAW RF filter device technology, design methodology, packaging, and in improving RF SAW substrates.

This paper focuses on the recent and ongoing advances in RF SAW filter substrates. In the late 1970’s Lewis [1] proposed constructing SAW filters employing bulk waves skimming/trapped along the surface of the substrate. The coupling coefficient for such waves was quite high and the TCF moderate. In the years following, Lewis’ work led the 36° LiTaO3 (LT) being used to produce SAW RF filters in cellular handsets employing leaky SAW (LSAW) substrates.

Two decades after Lewis’ work, an improved orientation of LT was introduced. Hashimoto et al. realized that the performance of the substrate could be improved if its orientation was selected in conjunction with the thickness of the aluminum electrodes [2]. By collectively selecting both the orientation and metal thickness, the Q of the shunt resonance was improved. This was done by reducing the bulk wave leakage of LSAW propagation. In the years following, 42° LT found wide spread application in SAW RF filters for cellular handsets.

Nearly ten years after the introduction of SAW RF filters using 42° LT, Naumenko introduced the concept of applying the work of Hashimoto et al. to improve the Q of a SAW transducer simultaneously at the transducer’s resonance and anti-resonance, Qr and Qar, respectively [3]. This had the result of increasing the y-rotation of the crystal for a particular metal thickness. For example, for a relative aluminum thickness of 10% of an IDT period, the desired y-rotation of LT increased to about 48°. Similar research was performed by Naumenko et al. [4] on LiNbO3 (LN).

Today, SAW RF filters for cellular handsets are dominated by devices fabricated on LT with y-rotations varying between 39° and 48°. It is common practice today to consider the metatization type, thickness, and filter specification when selecting the orientation, or rotation, of LT.

Further advances in RF SAW filter insertion loss and skirt steepness will require the consideration of other factors. The most significant of these will be the length (L) and width (W) of IDTs. How these additional factors impact the Q of a SAW resonator is discussed in general terms in a subsequent section of this paper.

In addition, other new ongoing advances in SAW RF substrates are being developed. Two such examples are pyroelectric suppression and temperature compensation. The pyroelectric effect of LT has long been a burden to achieving higher yields and lower costs for SAW RF filters. Recently, a process has been introduced to suppress the pyroelectric character of LT. A brief summary of the impact on device performance and on the reduction of the pyroelectric effect is presented.

Perhaps the most exciting development in advancing the performance SAW RF filter substrates is temperature compensation. Recently, processes have been developed that provide room temperature, non-adhesive wafer-to-wafer and die-to-wafer bonding for a wide variety of semiconductor materials [5]. One such example is the process developed by Ziptronix. Using a proprietary process, direct bonding of multiple materials in previously difficult combinations is now possible. The spectrum of possibilities includes combinations of piezoelectrics, such as LT, on glass, quartz, or Silicon. The bonding of a variety of other materials are also possible, and is not restricted by the need to find a lattice match between the crystals.

By bonding LT to lower TCE materials, such as glass, quartz, or Silicon, the TCF of the resulting filter is dramatically reduced. The resulting TCF, of SAW filter fabricated on these new substrates, can exceed that obtained by temper-
Substrate compensated FBAR devices in production today. Substrates constructed by combinations of LT and Silicon have been investigated in detail. The results of this work are discussed.

II POMNENT CHARACTERISTICS FOR RF SAW SUBSTRATES

The most prominent characteristics of a SAW RF filter substrate are the coupling coefficient, temperature coefficient of frequency (TCF) and Q.

1. \( Q_r \): The Q at resonance.
2. \( Q_{ar} \): The Q at anti-resonance.
3. \( K_{sq} \): The coupling coefficient.
4. TCF: The temperature coefficient of frequency.

The definition of coupling coefficient is given by eqn (1).

\[
K_{sq} = \frac{\pi^2}{4} \frac{f_{ar} - f_r}{f_{ar}}
\]

Based upon the principles of ladder filter design, eqn (1) may be used to determine a theoretical limit to the bandwidth of such filters. This theoretical maximum is stated below in eqn (2).

\[
\frac{\text{BW}}{f_c} \approx 0.4 \cdot K_{sq}
\]

Table 1: Typical TCF values for y-rotated cuts of LT and LN.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>TCF (ppm/°C)</th>
<th>BW Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>42-48° LT</td>
<td>-47</td>
<td>1.08</td>
</tr>
<tr>
<td>76° LN</td>
<td>-75</td>
<td>1.73</td>
</tr>
</tbody>
</table>

The bandwidth requirements for cellular handset filter applications has resulted in the wide spread use of y-rotated cuts of LT, and occasional use of y-rotated cuts of LN. The coupling coefficients for y-rotated orientations of LT and LN are illustrated in Fig 1.

Historically, orientations of LT have become more widely accepted in the marketplace. The popularity of LT over LN orientations is largely the result of the superior TCF of LT. Table I lists typical values for the TCFs of y-rotated orientations of LT and LN.

TCF has the effect of reducing the usable bandwidth of a filter. The relative reductions of bandwidth for y-rotated orientations of LT and LN are also listed in Table I, for a temperature span of -30°C to +85°C.

To understand how resonator Q effects the performance of an RF filter, it is useful to examine how an RF ladder filter is constructed using SAW resonators. Ladder filters are constructed using a plurality of series and shunt, one port SAW resonators, Fig 2 (a). The series elements approximate a low pass filter while the shunt elements approximate a high pass filter response, Fig 2 (b). The plurality of series and shunt resonators produce a band pass filter response, Fig 2 (c). Note that losses at the anti-resonance of the shunt elements and the resonance of the series elements will degrade the insertion loss of the ladder filter. Meanwhile, the steepness of the low frequency skirt of the filter is determined by the Q of the shunt resonators’ resonance, \( Q_r \), and the steepness of the high frequency skirt of the filter is determined by the Q of the series resonators’ anti-resonance, \( Q_{ar} \).

Since each filter specification has different requirements with respect to insertion loss, low skirt steepness, and high skirt steepness, it is important to select the proper material and substrate orientation so as to best meet the filter specification.

This was the primary motivation of the recent works by Hashimoto et al. [2] and Naumenko et al. [3]. These works sought to minimize the BAW leakage of the leaky SAW in y-rotated orientations of LT and LN. The reduction of BAW leakage requires that both the orientation and metal thickness be selected appropriately.

Figs 3 and 4 summarize the results of the research done by Hashimoto et al. [2] and Naumenko et al.[3, 4]. As the thickness of the electrodes is varied the orientation of LT and LN which produces the lowest BAW leakage also varies. This confirms the earlier statement that material, orientation, and metal thickness must each be carefully selected in order to
obtain the desired result of reduced BAW leakage.

An additional benefit of the work of Hashimoto et al. [2] was an increase in the coupling coefficient on LT. Those authors found that their embodiment for decreasing BAW leakage also had the benefit of increased coupling.

To illustrate the insertion loss which is obtainable from the various orientations of LT and LN, a probable filter structure was designed and tested. Fig 5 illustrates the structure of the die. The filter is composed of two T-sections. The input/output (i/o) pads as well as the ground pads are each labeled in Fig 5.

The frequency response of filter designs for 42° LT, 46° LT, 48° LT, and 76° LN are illustrated in Fig 6. The Aluminum thickness of each of the LT filters was h/2p=10%, and 5.5% for the filter on 75° LN. With the exception of differences in insertion loss and in skirt steepness, the frequency responses of the filters illustrated in Fig 6 are generally similar.

Table 2 offers a comparison of the minimum insertion losses for each of these filters. Each of these filters exhibit

Fig 7 compares the passband performance of each filter to that of 42° LT. From this figure, some observations can be made.

- 46° and 48° LT have improved insertion loss with respect to 42° LT, with 48° LT producing the best results for an Aluminum thickness of h/2p = 10%.
- 46° and 48° LT have improved skirt steepness with respect to 42° LT, with 48° LT producing the best results for an Aluminum thickness of h/2p = 10%.
- The insertion loss to the right of center frequency is favored by the LT filters, while that to the left of center frequency is favored by 76° LN.
- Each of the LT filters has superior skirt steepness as compared to the filter on 76° LN.

Figure 2: (a) Representative admittances of series and shunt impedance elements. (b) Representative filtering characteristics of series and shunt impedance elements. (c) Representative filter characteristic of a SAW ladder filter, composed of 2 series and 2 shunt impedance elements.

Figure 3: Effective propagation losses, in dB/2p, at resonance and anti-resonance plotted versus y-rotation for Al thickness of h/2p = 6, 8, 10, and 11% for y-rotated LT.
very low insertion losses. Their insertion losses differ by a few tenths of dB.

It is notable that the LN filter with an aluminum thickness of 5.5% is not particularly more lossy than the LT filters with aluminum thicknesses of 10%. This raises the question: What are the important individual contributors to the insertion loss of these filters? It would be convenient if the losses could be fully explained by BAW leakage and electrode resistance. However, the situation is more complicated than that. There are other loss mechanisms that contribute to a significant portion of the filters’ insertion losses. An examination of other loss mechanisms and contributors to the reduction of resonator Q can be useful.

III LOSS MECHANISMS IN RF SAW FILTERS

There are several contributors to the Q of an IDT, or one port SAW resonator. One of these has already been discussed in much detail; BAW leakage. Although a discussion of these is not strictly dependent upon the choice of SAW substrate, these loss mechanisms are impacted by the choice of substrate. Thus a discussion of additional loss mechanisms is merited.

For conceptual purposes, RF SAW filter losses may be separated into different categories. The itemized list below summarizes the largest contributors to Q in leaky SAW (LSAW) resonators.

- $Q_L$: Represents the frequency dependent bulk wave leakage into the substrate.
- $Q_S$: Represents the frequency dependent spectral radiation losses into the substrate.
- $Q_D$: Represents the effect of the dielectric losses of the substrate.
- $Q_R$: Represents the effect of the thin film resistance of the metalization.
Figure 7: Passband comparisons of four equivalent ladder filters on (a) 42° LT and 46° LT, (b) 42° LT and 48° LT, and (c) 42° LT and 76° LN

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Loss (dB)</th>
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<tbody>
<tr>
<td>42° LT</td>
<td>-1.11</td>
</tr>
<tr>
<td>46° LT</td>
<td>-0.93</td>
</tr>
<tr>
<td>48° LT</td>
<td>-0.84</td>
</tr>
<tr>
<td>76° LN</td>
<td>-1.07</td>
</tr>
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</table>

Table 2: Minimum loss of four ladder filters.

- \( Q_G \): Represents the losses associated with the transverse leakage of energy from the SAW waveguide.

These contributors of the finite \( Q \) of LSAW resonators do not necessarily degrade the \( Q \) at both resonance and anti-resonance. Some contributors effect only the resonant \( Q \) while others, only the anti-resonant \( Q \). This is summarized below by eqns [4-5].

\[
\frac{1}{Q_r} \approx \frac{1}{Q_L(f_r)} + \frac{1}{Q_D(f_r)} + \frac{1}{Q_G(f_r)} + \frac{1}{Q_h(f_r)}
\]

\[
\frac{1}{Q_{ar}} \approx \frac{1}{Q_L(f_{ar})} + \frac{1}{Q_S(f_{ar})} + \frac{1}{Q_G(f_{ar})} + \frac{1}{Q_D(f_{ar})}
\]

Each of these contributors to \( Q \) degradation are significant in LSAW resonators. For the purpose of improving the state of the art in LSAW substrates/filters, it is important to understand how the various contributors to \( Q \) are effected by substrate orientation as well as device structure.

\( BAW \) Leakage - \( Q_L \)

While the BAW leakage has been discussed in previous paragraphs, some further discussion is merited.

The BAW leakage component of \( Q \) may be investigated by theoretical means. For example, the admittance of a finite length one port resonator may be calculated from the principles of strip admittance [8, 7]. This calculation ignores 2D effects. If the dielectric and resistive losses are not included, the resonant \( Q \) will be representative of BAW leakage. Fig 3 illustrates the result of calculating the effective leakage losses in an infinitely long LSAW resonator on various orientation of LT and various thicknesses of Aluminum, at a duty factor of 50%.

An additional caveat in the implementation of practical filters, is that the BAW leakage of the \( y \)-rotated LSAW orientations of LT and LN increased for waves which propagate at angles oblique to the electrodes. Since practical filters have finite apertures, they will generate waves over a finite angular spectrum. This angular spectrum increases as the aperture of the resonator decreases. Thus, it is important to characterize how the leakage varies with the oblique angle of propagation.

Fig 8 illustrates how the effective propagation loss due to leakage varies with the angle of oblique propagation on both (a) 48° LT with \( h/2p=10\% \), and (b) 76° LN with \( h/2p=5.5\% \).

The BAW leakage varies very rapidly with oblique propagation angle. This is of great importance since practical RF filters have finite apertures typically in the range of 10 to 50 wavelengths. Thus, 2D effects must be considered. Fig. 8 illustrates how the leakage varies with oblique propagation angle. Note that the BAW leakage on 76° LN is superior for the ideal case of propagation parallel to the x-axis, as compared to 48° LT. However, at oblique angles the BAW leakage grows much more rapidly for 76° LN for 48° LT.
The treatment of these losses has been presented by Epcos [10].

Dielectric losses is easily determined by evaluating the Q and Q

been characterized for a 1D LSAW resonator the effect of

In general, it is possible to reduce the losses due to leakage by increasing the aperture of LSAW resonators on y-rotated orientations of LT or LN.

**Spectral BAW Radiation - Q_s**

The spectral component represents the slow shear BAW radiation. This has the effect of producing a broad band parasitic conductance in parallel with the LSAW resonator.

The spectral contribution to the anti-resonant Q may be evaluated directly by examining the Q_ar for a finite length 1D LSAW resonator for the special case where resistive and dielectric losses are excluded and the resonator’s duty factor and metal thickness are chosen to result in negligible BAW leakage (i.e. Q_L \gg Q_ar). Such a special case is represented by an Aluminum thickness of h/p=8% on 48°LT with a duty factor of 50%. Figure 9 illustrates this example. The analysis of finite length LSAW one port resonators and their Q has been analyzed using the approach reported by Koskela et al. [8].

The spectral component dominates Q_ar in this example (Fig. 9). From this special case, we may approximate the spectral contribution for orientations in the vicinity of 48°LT with metal thicknesses near h/p=8% and duty factors near 50%. A simple fit to Q_ar in Fig 9 produced the result in eqn (6).

\[ Q_S \approx 24 \cdot \frac{L}{2p} + 250 \]  

(6)

From eqn 6, it may be concluded that Q_S may be improved by increasing the length of the IDT.

**Dielectric & Resistive Losses - Q_D and Q_R**

Given that the leakage and spectral contributions have been characterized for a 1D LSAW resonator the effect of dielectric losses is easily determined by evaluating the Q_r and Q_ar in the presence of dielectric losses. An excellent treatment of these losses has been presented by Epcos [10].

The effect of finite resistivity of the electrodes and bus bars is well understood. The analysis by Lakin [11] and/or Wright [12] is sufficient for the purpose of evaluating the effect of finite resistance on LSAW resonator Q.

**Waveguide Losses - Q_G**

The waveguide losses are intended to include the effect of the planar 2D structure of SAW/LSAW resonators. The 2D structure of the resonators introduces 2 effects with respect to the device’s Q.

- Oblique propagation: Resonators with a finite aperture will radiate energy both normally and obliquely. That BAW leakage characteristically increases parabolically with the angle of oblique propagation has been discussed in a prior paragraph.

- Guide Leakage: Resonators with finite apertures are able to support acoustic modes. These modes often leak from the acoustic waveguide. This has the effect of reducing the Q of the resonator.

- Additional modes: More than one acoustic mode usually exists. These additional modes produce parasitic resonances which will degrade the overall Q of the resonator. Particularly the resonant Q.

In recent years, the effects of the finite aperture on resonator performance for SAW devices has been introduced [13, 14]. This approach has not yet been shown to be accurate for LSAW resonators, and is further restricted to substrate orientations whose anisotropy is convex in nature. Koskela et al. developed a phenomenological model to study the leakage of energy from a LSAW waveguide on y-rotated orientations of LT [9]. Rather than apply these impressive works, the authors have chosen to apply more approximate methods to determine qualitative relationships between wave guide losses and device geometries such as duty factor and/or aperture.

While not robust, if the analysis is restricted to devices with a narrow angular spectrum of LSAW radiation, it is possible to apply a scalar wave theory to resonators to determine qualitative trends. The results are not conclusive, but the indicated trends can be useful in filter design.

For the scalar wave theory, the anisotropy of the resonant velocity, v_R(\theta), may be characterized by a parabolic approximation, eqn (7).

\[ v_R(\theta) = v_R(0) \cdot (1 + \beta \cdot \theta^2) \]  

(7)

That the values for \beta for both the LT and LN orientations, Table 3, are negative, and less than -0.5, confirm the concave nature of the velocity on these substrates. The anisotropy of LT and LN in Table 3 correspond the the velocity at resonance.

Due the the extreme concave nature of the LSAW velocities for y-rotated orientations of LT, transducer region velocities which are less than the bus bar velocity will necessarily
produce leaky waveguide propagation. Transducer velocities greater than the bus bar velocity may produce guided modes.

A typical dependence a transducer’s resonant and anti-resonant velocity on duty factor for a y-rotated orientation of LT is illustrated in Fig 10. Also illustrated are the velocities of the LSAW under the bus bar and that of the generating BAW. The velocities in Fig 10 correspond to non-oblique propagation.

From Fig 10, it may be concluded that guide leakage at anti-resonance is less than that at resonance. This is verified by examination of the admittance plotted in Fig 11. A bulge in the admittance is recognizable between 1840 and 1890 MHz. This bulge certainly extends to lower frequencies, but is not clearly evident due larger contribution of the resonance. What is evident is that the bulge diminishes rapidly as the anti-resonant frequency is approached. Just above the anti-resonance, the bulge appears to disappear completely.

Given that higher transducer velocities produce reduced waveguide leakage, it is reasonable to expect less waveguide leakage as the duty factor of the resonators transducer is reduced. This has been confirmed by work at Fujitsu by Matsuda et al, [15] and Tsutsumi et al. [16].

Applying the scalar wave theory in combination with the parabolic approximation, the loss of an obliquely propagating wave reflecting at the boundary between the transducer and bus bar regions has been calculated at resonance, Fig 12. The dependence of the reflection’s loss on the oblique propagation angle is illustrated by Fig 13.
Assuming that the shape of the lowest order leaky waveguide mode may be approximated by \( \cos(\pi \cdot y/W) \), for \(-W/2 < y < +W/2\) and \(W\) being the transducer’s aperture, the reflection loss in Fig 13 may be used to determine an approximate value for the waveguide leakage. Fig 14 plots this resulting approximation to the waveguide’s leakage as a function of the resonators aperture. As might be expected, the waveguide leakage decreases rapidly with aperture.

**Optimizing Filter Performance**

In order to further improve the performance of RF SAW filters on \(y\)-rotated orientation of LT it will be necessary to consider both 1st and 2nd order contributors to losses in these filters. There are several structural components which must be included for such consideration. A short list of the dominant structural components are given below.

- Piezoelectric material.
- Euler Angles of the substrate.
- Metal Composition: For example, Al, Au, Cu, etc.
- Metal Thickness \((h)\): or relative metal thickness \(h/p\), where \(p\) is the period of the electrode.
- Duty Factor \((a/p)\): where \(a\) is the width of the electrode, and \(p\) is the period.
- Transducer Length \((L)\): or relative length in wavelengths, \(L/2p\).
- Transducer Aperture \((W)\): or relative width in wavelengths, \(W/2p\).

The list above includes both the 1D and 2D structure of the filter’s planar structure. In the future, an analysis of the filter’s 2D planar structure is expected to become common practice when designing competitive SAW RF filters.

**IV PYROELECTRIC SUPPRESSION**

The pyroelectric nature of LT is a serious concern for the manufacture of SAW devices. A typical damage of a SAW filter is illustrated in Fig 15. The resulting damage to the frequency response of the filter is illustrated in Fig 16. Such frequency of such damage is not consistent from one design to another. In some designs the damage can be very common and result in significant yield problems.

A process for suppressing pyroelectric characteristic of LT has been developed and introduced into the market by Silicon Light Machines [6]. The adoption of this process has many obvious advantages. These advantages include:

- Allows manufacture of SAW filters free of temperature induced voltage spikes.
- Reduction in wafer loss during processing of SAW filters.
- Shortened SAW filter manufacturing cycle time.
- Higher quality SAW filters to address growing markets.
Figure 17: Pyro-suppressed LT dramatically reduces the voltage detected at 1mm above the surface of the wafer during temperature cycling.

The reduction in the pyroelectric effect is not total. However, it is very significant. Figure 17 illustrates the reduction of the DC field voltage detected at a distance of 1mm above the surface of a LT wafer during a temperature ramp of 140°C above ambient. The voltage detected at 1 mm above the surface of the wafer is reduced several orders of magnitude, and does not exceed 10 Volts.

Silicon Light Machines’ process for reducing the pyroelectric effect of LT is based upon making the LT wafers slightly conductive. The process applies a conductivity treatment to raw LT wafers, and is compatible with any cut of LT. The process has been successfully demonstrated on wafers with thicknesses of 0.5, 0.35, and 0.25 mm.

V Temperature Compensation

The market demands or new products, such as a US PCS duplexer, place requirements upon SAW technology which cannot be met by present SAW materials. The area of greatest potential for improvement of filter performance is in the temperature compensation of SAW RF filters.

In 1998, Sato et al. [17] reported on temperature compensated SAW devices fabricated on wafers constructed by directly bonding LT to glass. Filter TCFs as low as -6 ppm/°C were obtained. The process used by Sato et al. for performing the direct bonding of low TCE materials to LT was previously reported by Matsushita [18, 19, 20]. It is not known by the authors (Abbott et al.) if such wafers are commercially available from Matsushita, or if SAW products have been introduced into the market place which use this technology.

In 2002, Solal et al. [21] reported on a method to produce wafers constructed of a thin layer of LN directly bonded to Silicon. While the reduction of TCF was impressive, the resulting wafer had poor coupling, about half that expected.

Recently, processes have been developed that provide room temperature, non-adhesive wafer-to-wafer and die-to-wafer bonding for a wide variety of semiconductor materials. One such example is the process developed by Ziptronix [5], who is planning to introduce such wafers into the market place.

Using a proprietary process, bonding of multiple materials in previously difficult/impossible combinations is possible. The spectrum of possibilities includes combinations of piezoelectrics, such as LT, on glass, quartz, or Silicon. The bonding of a variety of other materials are also possible, and is not restricted by the need to find a lattice match between the crystals.

By bonding LT to lower TCE materials, such as glass, quartz, or Silicon, the TCF of the resulting filter is dramatically reduced. The resulting TCF, of SAW filter fabricated on these new substrates, can match, and possibly exceed, that obtained by temperature compensated FBAR devices in production today.

The structure of a typical bonded wafer is illustrated in Fig...
Figure 19: The completed bonded wafer is comprised of the low TCE material, a thin oxide layer (if needed), and the LT on top.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Low Side TCF ppm/°C</th>
<th>High Side TCF ppm/°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular LT</td>
<td>-44</td>
<td>-50</td>
</tr>
<tr>
<td>Bonded LT</td>
<td>-22</td>
<td>-35</td>
</tr>
<tr>
<td>FBAR</td>
<td>-17</td>
<td>-24</td>
</tr>
</tbody>
</table>

Table 4: TCF values three implementations of a US PCS TX full band filter.

19. Note that a thin oxide layer is required to bond LT or LN to the low TCE material (Quartz, Glass, Si, etc).

For comparison purposes, a US PCS TX full band filter has been designed and manufactured on both regular 48° LT and 48° LT bonded to a Silicon wafer (with a thin layer of SiO₂ between the wafers).

Each of these filters were measured over a temperature range of -30°C to +85°C. The results of these measurements are illustrated in Fig 20. The TCF data for each of the filters is summarized in Table 4. TCF data for a representative production FBAR filter is included in Table 4 for comparison.

The flip chipped SAW filter on bonded material has a significantly reduced TCF as compared to regular LT. Chip and wire versions of similar filters are improved even further (devices with TCFs as low as -12ppm/°C have been measured). The difference in TCF between chip and wire package and flip chip package of SAW filters is the result of the thermal expansion of the flip chip package being greater than that of the low TCE bonded wafer. Thus, the process of flipping the SAW die partially counteracts the temperature compensation of the bonded wafer. Because the propagation direction for the FBAR is normal to the wafer surface, this issue is not present in the implementation of the FBAR filter. Thus, flip chip packaging of an FBAR filter is not expected to play as significant a role in the resulting TCF of the filter.

It is of interest to note, that because the thickness of LT, for the bonded wafer, is thin in comparison to the planar dimensions of a typical filter, the coupling coefficient of the bonded wafer is increased (due to a decrease in IDT capacitance). This increase is due to the fact that the LT has a much higher dielectric constant than the low TCE material it is bonded to. Preliminary results indicate that $K_{sq}$ increased from about 9% to about 11% for 48° LT.

Figure 20: Comparison of temperature drift for (a) full band RF SAW TX filter for US PCS fabricated on normal LT wafer and (b) full band RF SAW TX filter for US PCS fabricated on LT wafer bonded for temperature compensation.

VI Conclusions

The last decade has seen impressive advances in reducing the insertion loss and improving the skirt steepness of RF SAW filters [2, 3]. An overview of this work in reducing the BAW leakage of y-rotated orientations of LT, and which has significantly contributed to these advances, has been presented.

Other loss mechanisms and some possibilities for overcoming them have been discussed. These loss mechanisms include resistive losses, dielectric losses, and as well as losses associated with the finite 2D planar structure of SAW RF filters.

In addition, new advances in RF SAW substrates are now emerging. These include suppression of the pyroelectric effect of LT, and temperature compensation of LT by direct wafer bonding at room temperature. Each of these advances were discussed in general terms, and detailed results of their application to the manufacture of SAW devices was reported.
VII ACKNOWLEDGEMENTS

The authors would like to acknowledge the technical discussions of Josh Zepes and Kamran Cheema of Sawtek. Additionally, the authors would like to acknowledge the contributions of Ziptronix and Silicon Light Machines in developing and introducing temperature compensated and pyro-suppressed LT into the market place.

REFERENCES


