

ACOUSTIC WAVE DEVICES

CROSS-REFERENCE TO RELATED APPLICATION(S)

[0001] This application claims priority to U.S. Provisional Application No. 62/746,512 filed October 16, 2018, entitled ACOUSTIC WAVE DEVICES, the disclosure of which is hereby expressly incorporated by reference herein in its entirety.

BACKGROUND

Field

[0002] The present disclosure relates to acoustic wave devices such as surface acoustic wave (SAW) devices.

Description of the Related Art

[0003] A surface acoustic wave (SAW) resonator typically includes an interdigital transducer (IDT) electrode implemented on a surface of a piezoelectric layer. Such an electrode includes two interdigitized sets of fingers, and in such a configuration, the distance between two neighboring fingers of the same set is approximately the same as the wavelength λ of a surface acoustic wave supported by the IDT electrode.

[0004] In many applications, the foregoing SAW resonator can be utilized as a radio-frequency (RF) filter based on the wavelength λ . Such a filter can provide a number of desirable features.

SUMMARY

[0005] In accordance with some implementations, the present disclosure relates to an acoustic wave device that includes a quartz substrate having a first surface, and a piezoelectric plate formed from LiTaO₃ or LiNbO₃ and including a first surface configured to support a surface acoustic wave and a second surface in engagement with the first surface of the quartz substrate. The second surface is a minus surface resulting from crystal structure orientation of the piezoelectric plate. The acoustic wave device further includes an interdigital transducer electrode formed on the first surface of the piezoelectric plate and

configured to provide transducer functionality associated with the surface acoustic wave.

[0006] In some embodiments, the crystal structure orientation of the piezoelectric plate can include Euler angles (0° , $90^\circ < \theta < 270^\circ$, 0°). In some embodiments, the first surface of the quartz substrate can be a plus surface resulting from crystal structure orientation of the quartz substrate. The crystal structure orientation of the quartz substrate can include Euler angles (ϕ , $90^\circ < \theta < 270^\circ$, ψ), with the angle ϕ having a value in a range of $0^\circ \leq \phi < 180^\circ$, and the angle ψ having a value in a range of $0^\circ \leq \psi < 180^\circ$. The angle ϕ can have a value of, for example, 0° . The angle ψ can have a value of, for example, 0° .

[0007] In some embodiments, the first surface of the quartz substrate can be a minus surface resulting from crystal structure orientation of the quartz substrate. The crystal structure orientation of the quartz substrate can include Euler angles (ϕ , $-90^\circ < \theta < 90^\circ$, ψ), with the angle ϕ having a value in a range of $0^\circ \leq \phi < 180^\circ$, and the angle ψ having a value in a range of $0^\circ \leq \psi < 180^\circ$. The angle ϕ can have a value of, for example, 0° . The angle ψ can have a value of, for example, 0° .

[0008] In some embodiments, the first surface of the quartz substrate can be an unpolarized surface resulting from crystal structure orientation of the quartz substrate. The crystal structure orientation of the quartz substrate can include Euler angles (ϕ , 90° , ψ) or (ϕ , -90° , ψ), with the angle ϕ having a value in a range of $0^\circ \leq \phi < 180^\circ$, and the angle ψ having a value in a range of $0^\circ \leq \psi < 180^\circ$. The angle ϕ can have a value of, for example, 90° , and the angle ψ can have a value of, for example, 90° .

[0009] In some embodiments, the piezoelectric plate can be formed from LiTaO₃ and the quartz substrate can include Euler angles (0° , 10° - 80° , 0°), (0° , 100° - 170° , 0°), (0° , 190° - 260° , 0°) or (0° , 280° - 350° , 0°).

[0010] In some embodiments, the piezoelectric plate can be formed from LiNbO₃ and the quartz substrate can include Euler angles (0° , 5° - 85° , 0°), (0° , 95° - 175° , 0°), (0° , 185° - 265° , 0°) or (0° , 275° - 355° , 0°).

[0011] In some embodiments, the piezoelectric plate can be formed from LiTaO₃ and the quartz substrate can include Euler angles (0° , 5° - 53° , 90°), (0° , 127° - 175° , 90°), (0° , 185° - 233° , 90°) or (0° , 307° - 355° , 90°).

[0012] In some embodiments, the piezoelectric plate can be formed from LiNbO_3 and the quartz substrate can include Euler angles (0° , 0° - 52° , 90°), (0° , 126° - 180° , 90°), (0° , 180° - 232° , 90°) or (0° , 306° - 360° , 90°).

[0013] In some embodiments, the piezoelectric plate can be formed from LiTaO_3 or LiNbO_3 and the quartz substrate can include Euler angles (0° , 0° - 360° , 0° - 60°) or (0° , 0° - 360° , 120° - 180°). In some embodiments, the piezoelectric plate can be formed from LiTaO_3 or LiNbO_3 and the quartz substrate can include Euler angles (0° , 0° - 360° , 0° - 45°) or (0° , 0° - 360° , 135° - 180°).

[0014] In some embodiments, the acoustic wave device can further include first and second reflectors implemented on the first surface of the piezoelectric plate and positioned on first and second sides of the interdigital transducer electrode.

[0015] In some embodiments, thickness of the piezoelectric plate can be in a range of 0.04λ to 1.5λ , with the quantity λ being wavelength of the surface acoustic wave. In some embodiments, the thickness of the piezoelectric plate can be in a range of 0.06λ to 1.0λ .

[0016] In some teachings, the present disclosure relates to a method for fabricating an acoustic wave device. The method includes forming or providing a quartz substrate having a first surface. The method further includes forming or providing a piezoelectric plate with LiTaO_3 or LiNbO_3 to include a first surface configured to support a surface acoustic wave and a second surface being a minus surface resulting from crystal structure orientation of the piezoelectric plate. The method further includes coupling the piezoelectric plate with the quartz substrate such that the minus surface of the piezoelectric plate engages the first surface of the quartz substrate.

[0017] In some embodiments, the method can further include forming an interdigital transducer electrode on the first surface of the piezoelectric plate to provide transducer functionality associated with the surface acoustic wave.

[0018] In some embodiments, the crystal structure orientation of the piezoelectric plate can include Euler angles (0° , $90^\circ < \theta < 270^\circ$, 0°). In some embodiments, the first surface of the quartz substrate can be a plus surface, a minus surface or an unpolarized surface resulting from crystal structure orientation of the quartz substrate.

[0019] In some embodiments, the first surface of the quartz substrate can be a plus surface, and the quartz substrate can include Euler angles (ϕ , $90^\circ < \theta < 270^\circ$, ψ); be a minus surface, and the quartz substrate can include Euler angles (ϕ , $-90^\circ < \theta < 90^\circ$, ψ); or be an unpolarized surface, and the quartz substrate can include Euler angles (ϕ , 90° , ψ) or (ϕ , -90° , ψ). The angle ϕ can have a value in a range of $0^\circ \leq \phi < 180^\circ$, and the angle ψ can have a value in a range of $0^\circ \leq \psi < 180^\circ$.

[0020] In some embodiments, the forming or providing of the piezoelectric plate can include forming the piezoelectric plate after the coupling of the piezoelectric plate with the quartz substrate. The coupling of the piezoelectric plate with the quartz substrate and the forming of the piezoelectric plate can include bonding a thick piezoelectric layer to the quartz substrate, followed by thinning the thick piezoelectric layer to result in the piezoelectric plate engaged to the quartz substrate. The thinning of the thick piezoelectric layer can include a polishing process.

[0021] In some embodiments, the forming or providing of the piezoelectric plate can include forming the piezoelectric plate before the coupling of the piezoelectric plate with the quartz substrate. The coupling of the piezoelectric plate with the quartz substrate and the forming of the piezoelectric plate can include attaching a thick piezoelectric layer to a handling substrate, followed by thinning the thick piezoelectric layer to form the minus surface of the piezoelectric plate, followed by bonding the minus surface of the piezoelectric plate to the quartz substrate. The coupling of the piezoelectric plate with the quartz substrate and the forming of the piezoelectric plate can further include removing the handling substrate to expose the first surface of the piezoelectric plate.

[0022] In some embodiments, the handling substrate can include a silicon substrate. In some embodiments, the attaching of the thick piezoelectric layer to the handling substrate can include bonding the thick piezoelectric layer to the handling substrate. In some embodiments, the thinning of the thick piezoelectric layer can include a polishing process while the thick piezoelectric layer is attached to the handling substrate. In some embodiments, the removing of the handling substrate can include an etching process.

[0023] In a number of implementations, the present disclosure relates to a radio-frequency filter that includes an input node for receiving a signal, and an output node for providing a filtered signal. The radio-frequency filter further includes an acoustic wave device implemented to be electrically between the input node and the output node to generate the filtered signal. The acoustic wave device includes a quartz substrate with a first surface, and a piezoelectric plate formed from LiTaO_3 or LiNbO_3 and having a first surface configured to support a surface acoustic wave and a second surface in engagement with the first surface of the quartz substrate. The second surface is a minus surface resulting from crystal structure orientation of the piezoelectric plate.

[0024] In some embodiments, the radio-frequency filter can further include first and second interdigital transducer electrodes formed on the first surface of the piezoelectric plate. The first interdigital transducer electrode can be electrically connected to the input node and the second interdigital transducer electrode can be electrically connected to the output node.

[0025] In some implementations, the present disclosure relates to a radio-frequency module that includes a packaging substrate configured to receive a plurality of components, and a radio-frequency circuit implemented on the packaging substrate and configured to support either or both of transmission and reception of signals. The radio-frequency module further includes a radio-frequency filter configured to provide filtering for at least some of the signals. The radio-frequency filter includes an acoustic wave device having a quartz substrate with a first surface, and a piezoelectric plate formed from LiTaO_3 or LiNbO_3 and having a first surface configured to support a surface acoustic wave and a second surface in engagement with the first surface of the quartz substrate. The second surface is a minus surface resulting from crystal structure orientation of the piezoelectric plate.

[0026] In some implementations, the present disclosure relates to a wireless device that includes a transceiver, an antenna, and a wireless system implemented to be electrically between the transceiver and the antenna. The wireless system includes a filter configured to provide filtering functionality for the wireless system. The filter includes an acoustic wave device having a quartz substrate with a first surface, and a piezoelectric plate formed from LiTaO_3 or LiNbO_3 and having a first surface configured to support a surface acoustic wave

and a second surface in engagement with the first surface of the quartz substrate. The second surface is a minus surface resulting from crystal structure orientation of the piezoelectric plate.

[0027] In some teachings, the present disclosure relates to a method for fabricating an acoustic wave device. The method includes attaching a first surface of a piezoelectric layer to a handling substrate, and performing a thinning operation on the piezoelectric layer to expose a second surface of a reduced-thickness piezoelectric layer attached to the handling substrate. The method further includes bonding the second surface of the reduced-thickness piezoelectric layer to a first surface of a permanent substrate, and removing the handling substrate from the reduced-thickness piezoelectric layer.

[0028] In some embodiments, the removing of the handling substrate from the reduced-thickness piezoelectric layer can expose the first surface that was attached to the handling substrate, with the first surface being configured to support a surface acoustic wave. The method can further include forming an interdigital transducer electrode on the first surface of the reduced-thickness piezoelectric layer to provide transducer functionality associated with the surface acoustic wave.

[0029] In some embodiments, an assembly of the acoustic wave device and the respective interdigital transducer electrode can be one of an array of similar assemblies implemented as a wafer. The method can further include singulating the wafer to provide a plurality of acoustic wave devices.

[0030] In some embodiments, the handling substrate can include a silicon substrate. In some embodiments, the permanent substrate can include a quartz substrate.

[0031] In some embodiments, the piezoelectric layer can be formed from LiTaO_3 or LiNbO_3 with a crystal structure orientation such that the second surface of the reduced-thickness piezoelectric layer is a minus surface. The crystal structure orientation of the piezoelectric plate can include Euler angles (0° , $90^\circ < \theta < 270^\circ$, 0°).

[0032] In some embodiments, the first surface of the permanent substrate can be a plus surface, a minus surface or an unpolarized surface resulting from crystal structure orientation of the permanent substrate. In some embodiments, the first surface of the permanent substrate can be a plus surface,

and the permanent substrate can include Euler angles (ϕ , $90^\circ < \theta < 270^\circ$, ψ); be a minus surface, and the permanent substrate can include Euler angles (ϕ , $-90^\circ < \theta < 90^\circ$, ψ); or be an unpolarized surface, and the permanent substrate can include Euler angles (ϕ , 90° , ψ) or (ϕ , -90° , ψ). The angle ϕ can have a value in a range of $0^\circ \leq \phi < 180^\circ$, and the angle ψ can have a value in a range of $0^\circ \leq \psi < 180^\circ$.

[0033] In accordance with some implementations, the present disclosure relates to a wafer assembly that includes a piezoelectric layer having a first surface and a second surface. The wafer assembly further includes a handling substrate attached the first surface of the piezoelectric layer, and a permanent substrate attached to the second surface of the piezoelectric layer. The handling substrate is selected to be removable to expose the first surface of the piezoelectric layer while the piezoelectric layer is attached to the permanent substrate.

[0034] In some embodiments, the handling substrate can be a silicon substrate. In some embodiments, the permanent substrate can be a quartz substrate.

[0035] In some embodiments, the piezoelectric layer can be a reduced-thickness piezoelectric layer resulting from a thinning operation on a thick piezoelectric layer having its first surface attached to the handling wafer and without the permanent substrate. In some embodiments, the first surface of the piezoelectric layer can be bonded to the handling substrate with a first bond strength, and the second surface of the piezoelectric layer can be bonded to the permanent substrate with a second bond strength. The first bond strength between the piezoelectric layer and the handling substrate can be greater than the bond strength between the piezoelectric layer and the permanent substrate, with the first bond strength allowing the thinning operation to be performed without damage to the piezoelectric layer. For example, the first bond strength between the piezoelectric layer and the handling substrate can be greater than the second bond strength between the piezoelectric layer and the permanent substrate by at least an order of magnitude.

[0036] In some embodiments, the piezoelectric layer can be formed from LiTaO_3 or LiNbO_3 with a crystal structure orientation such that the second surface of the reduced-thickness piezoelectric layer is a minus surface. The

crystal structure orientation of the piezoelectric plate can include Euler angles (0° , $90^\circ < \theta < 270^\circ$, 0°).

[0037] In some embodiments, the first surface of the permanent substrate can be a plus surface, a minus surface or an unpolarized surface resulting from crystal structure orientation of the permanent substrate. In some embodiments, the first surface of the permanent substrate can be a plus surface, and the permanent substrate can include Euler angles (ϕ , $90^\circ < \theta < 270^\circ$, ψ); be a minus surface, and the permanent substrate can include Euler angles (ϕ , $-90^\circ < \theta < 90^\circ$, ψ); or be an unpolarized surface, and the permanent substrate can include Euler angles (ϕ , 90° , ψ) or (ϕ , -90° , ψ). The angle ϕ can have a value in a range of $0^\circ \leq \phi < 180^\circ$, and the angle ψ can have a value in a range of $0^\circ \leq \psi < 180^\circ$.

[0038] For purposes of summarizing the disclosure, certain aspects, advantages and novel features of the inventions have been described herein. It is to be understood that not necessarily all such advantages may be achieved in accordance with any particular embodiment of the invention. Thus, the invention may be embodied or carried out in a manner that achieves or optimizes one advantage or group of advantages as taught herein without necessarily achieving other advantages as may be taught or suggested herein.

BRIEF DESCRIPTION OF THE DRAWINGS

[0039] Figure 1 shows an example of a conventional structure of a surface acoustic wave (SAW) resonator including an interdigital transducer (IDT) electrode formed on a LiTaO_3 (LT) or LiNbO_3 (LN) and reflectors formed on both sides of the IDT electrode.

[0040] Figure 2 shows an example of a structure of a SAW resonator including a combination of an LT plate or an LN plate with a quartz substrate.

[0041] Figure 3 shows an enlarged and isolated plan view of the IDT electrode of the SAW resonator of Figure 2.

[0042] Figure 4 shows an actual measurement characteristic of a conventional SAW resonator manufactured by forming a copper (Cu) IDT electrode on a 42°YXLT ($(0^\circ, 312^\circ, 0^\circ)$ in Euler angle) substrate.

[0043] Figure 5 shows an actual measurement characteristic of a SAW resonator manufactured by combining a Cu electrode, a 42°YXLT ((0°, 132°, 0°) in Euler angle) plate, and a 42°45'Y90°X ((0°, 132°45', 90°) in Euler angle) quartz substrate.

[0044] Figures 6A-6H shows various combinations of an LT or LN plate with a quartz substrate.

[0045] Figures 7A and 7B show an example characterization of polarization and surface charge of a layer such as an LT or LN plate or quartz substrate.

[0046] Figures 8A and 8B show polarizations of example LT crystal orientations relative to a reference coordinate system.

[0047] Figures 9A and 9B show frequency characteristics of SAW resonators in which an aluminum electrode having a wavelength (λ) of 2 μ m and a thickness of 0.08 λ is formed on the (+) surface of a 20°-rotated Y-plate X-propagation LT ((0°, 110°, 0°) in Euler angle) and the (-) surface thereof ((0°, 290°, 0°) in Euler angle) respectively.

[0048] Figures 10A and 10B show frequency characteristics of SAW resonators in which the electrode of Figures 9A and 9B is formed on the (+) surface of a 42°-rotated Y-plate X-propagation LT ((0°, 132°, 0°) in Euler angle) and the (-) surface thereof ((0°, 312°, 0°) in Euler angle) respectively.

[0049] Figures 11A-11D show frequency characteristics of four combinations of the (+) and (-) surfaces of a 20°-rotated Y-plate X-propagation LT with the (+) and (-) surfaces of a 42°45'Y-plate 90°X-propagation quartz.

[0050] Figures 12A and 12B show an Euler angle dependence of the bandwidth and the impedance ratio for an SAW resonator formed according to four combinations of the (+) and (-) surfaces of a 20°-rotated Y-plate X-propagation LT with the (+) and (-) surfaces of a rotation 35°Y-plate 90°X-propagation to 60°Y-plate 90°X-propagation quartz.

[0051] Figures 13A and 13B show an Euler angle dependence of the bandwidth and the impedance ratio for an SAW resonator formed according to four combinations of the (+) and (-) surfaces of a rotation 10°X-propagation to 50°YX-propagation LT with the (+) and (-) surfaces of a 42°45'Y-plate 90°X-propagation quartz.

[0052] Figures 14A and 14B show an Euler angle dependence of the bandwidth and the impedance ratio for an SAW resonator formed according to four combinations of the (+) and (-) surfaces of a 25°-rotation Y-plate X-propagation LN with the (+) and (-) surfaces of a rotation 35°Y-plate 90°X-propagation to 60°Y-plate 90°X-propagation quartz.

[0053] Figures 15A and 15B show an LT-thickness dependence of the bandwidth and the impedance ratio for an SAW resonator having a +20YXLT-/ +42°45'Y90X quartz structure.

[0054] Figure 16 shows a θ dependence of the linear expansion coefficients in the X-direction (SAW propagation direction) and the Y-direction (direction 90-degree angled to the SAW propagation direction) of a (0°, θ , 0°) LT.

[0055] Figure 17 shows a θ dependence of the linear expansion coefficient in the X-direction (SAW propagation direction) and the Y-direction (direction 90-degree angled to the SAW propagation direction) of a (0°, θ , 0°) LN.

[0056] Figure 18 shows a θ dependence of the linear expansion coefficients in the X-direction and the Y-direction of a (0°, θ , 0°) quartz.

[0057] Figure 19 shows a θ dependence of the linear expansion coefficients in the X-direction and the Y-direction of a (0°, θ , 45°) quartz.

[0058] Figure 20 shows a θ dependence of the linear expansion coefficients in the X-direction and the Y-direction of a (0°, θ , 90°) quartz.

[0059] Figure 21 shows a ψ dependence of the linear expansion coefficients in the X-direction and the Y-direction of a (0°, 126°, ψ) quartz.

[0060] Figure 22 shows a ψ dependence of the linear expansion coefficients in the X-direction and the Y-direction of a (0°, 132°45', ψ) quartz.

[0061] Figure 23 shows a ψ dependence of the linear expansion coefficients in the X-direction and the Y-direction of a (0°, 145°, ψ) quartz.

[0062] Figures 24A-24C show an example of a process that can be utilized to obtain a combination of an LT or LN plate and a quartz substrate.

[0063] Figures 25A-25E show another example of a process that can be utilized to obtain a combination of an LT or LN plate and a quartz substrate.

[0064] Figure 26A shows an LT substrate damaged after a heat treatment of 20 hours at 200 °C subsequent to a bonding process of Figures 24A-24C.

[0065] Figure 26B shows an example of a substrate partially peeled due to a weak bond strength when the substrate is polished to 5 μ m during the process of Figures 24A-24C.

[0066] Figure 27A shows an LT surface obtained after an LT is bonded to a silicon substrate and then the LT is polished to a thickness of 0.3 μ m.

[0067] Figure 27B shows an LT surface obtained after a quartz substrate is bonded to the LT surface of the assembly of Figure 27A and then the silicon substrate is etched by plasma etching.

[0068] Figure 28 shows a frequency characteristic of an SAW resonator manufactured by a method similar to the example of Figures 25A-25E.

[0069] Figure 29 shows that in some embodiments, multiple units of SAW resonators can be fabricated while in an array form such as in a wafer form.

[0070] Figure 30 shows that in some embodiments, a SAW resonator having or more features as described herein can be implemented as a part of a packaged device.

[0071] Figure 31 shows that in some embodiments, the SAW resonator based packaged device of Figure 30 can be a packaged filter device.

[0072] Figure 32 shows that in some embodiments, a radio-frequency (RF) module can include an assembly of one or more RF filters.

[0073] Figure 33 depicts an example wireless device having one or more advantageous features described herein.

DETAILED DESCRIPTION OF SOME EMBODIMENTS

[0074] The headings provided herein, if any, are for convenience only and do not necessarily affect the scope or meaning of the claimed invention.

[0075] Frequency bands used for smart phones and the like include approximately 80 bands, which are close to each other, and thus filters and duplexers having a steep frequency characteristic are required or desired. Such filtering applications can include, for example, a ladder-filter structure, in which resonators employing a surface acoustic wave (SAW) or a bulk wave are arranged as a ladder. Accordingly, a resonator having a greater impedance ratio or a high Q is needed or desired to realize a filter or duplexer having a steep frequency characteristic.

[0076] Figure 1 shows an example of a conventional structure of a surface acoustic wave (SAW) resonator 10 including an interdigital transducer (IDT) electrode 12 formed on a LiTaO_3 (LT) or LiNbO_3 (LN) substrate 18, and reflectors 14, 16 formed on both sides of the IDT electrode 12.

[0077] Figure 2 shows an example of a surface acoustic wave (SAW) device 100 implemented as a SAW resonator. Such a SAW resonator can include a piezoelectric layer 104 formed of, for example, LiTaO_3 (also referred to herein as LT) or LiNbO_3 (also referred to herein as LN). Such a piezoelectric layer can include a first surface 110 (e.g., an upper surface when the SAW resonator 100 is oriented as shown) and an opposing second surface. The second surface of the piezoelectric layer 104 can be attached to, for example, a quartz substrate 112.

[0078] On the first surface 110 of the piezoelectric layer 104, an interdigital transducer (IDT) electrode 102 can be implemented, as well as one or more reflector assemblies (e.g., 114, 116). Figure 3 shows an enlarged and isolated plan view of the IDT electrode 102 of the SAW resonator 100 of Figure 2. It will be understood that the IDT electrode 102 of Figures 2 and 3 can include more or less numbers of fingers for the two interdigitized sets of fingers.

[0079] In the example of Figure 3, the IDT electrode 102 is shown to include a first set 120a of fingers 122a and a second set 120b of fingers 122b arranged in an interdigitized manner. In such a configuration, the distance between two neighboring fingers of the same set (e.g., neighboring fingers 122a of the first set 120a) is approximately the same as the wavelength λ of a surface acoustic wave associated with the IDT electrode 102.

[0080] In the example of Figure 3, various dimensions associated with the fingers are shown. More particularly, each finger (122a or 122b) is shown to have a lateral width of F , and a gap distance of G is shown to be provided between two interdigitized neighboring fingers (122a and 122b).

[0081] It is noted that the SAW resonator 100 of Figure 2 can be configured to provide a greater impedance ratio (e.g., by about 29dB) than the conventional SAW resonator 10 of Figure 1. For example, Figure 4 shows an impedance characteristic plot as a function of frequency for the SAW resonator 10 of Figure 1, and Figure 5 shows an impedance characteristic plot as a function of frequency for the SAW resonator 100 of Figure 2. For the plot of Figure 4,

impedance ratio ($20\log(Z_a/Z_r)$) is 51dB, where Z_r and Z_a are impedance values at resonant frequency f_r and antiresonant frequency f_a , respectively. For the plot of Figure 5, impedance ratio is 80dB which is 29dB greater than that of Figure 4.

[0082] In some implementations, the present disclosure relates to a technique for fabricating a SAW resonator 100 of Figure 2. Such a technique can allow a fabrication process to avoid or reduce the likelihood of undesirable effects. For example, when an LT or LN is bonded to a quartz substrate, damage may occur due to the thermal expansion difference between the LT or LN and the quartz substrate during a heat treatment process performed to enhance the bond strength. In another example, in a case where a bonded substrate is produced at a lower heat treatment temperature in order to avoid the damage, the bond strength may be weaker and thus the LT or LN may be cracked or peeled from the quartz substrate during a thinning process of the LT or LN plate.

[0083] In some embodiments, devices, structures and methods can be utilized to enhance the bond strength by optimally or selectively combining an orientation angle of LT or LN with an orientation angle of quartz substrate, and/or to support a manufacturing process when the bonding is weaker.

[0084] It is noted that a bandwidth of an acoustic wave filter depends on the electromechanical coupling coefficient (coupling coefficient) of a piezoelectric substrate used in the acoustic wave filter. Accordingly, a LiTaO₃ (LT) or LiNbO₃ (LN) substrate having a coupling coefficient necessary for the bandwidth of the filter is used.

[0085] In many applications, a resonator having a coupling coefficient satisfying the bandwidth of the filter while having a greater impedance ratio (higher Q) is desired. As described herein, combining a thin-plated LT or LN with a quartz substrate as shown in Figure 2 may provide a greater impedance ratio and a better temperature characteristic as shown in Figure 5.

[0086] In some embodiments, optimizing or selecting the polarity of the LT or LN piezoelectric thin plate and the polarity of the quartz substrate to be in a desirable relationship may provide an even broader bandwidth and an even greater impedance ratio. For example, bonding a minus (-) surface of the LT or LN with the quartz substrate may provide a broader bandwidth and a greater impedance ratio than bonding a plus (+) surface of the LT or LN with the quartz substrate. Examples of such polarities are described herein in greater detail.

[0087] In some embodiments, after bonding the minus surface of the LT or LN to the quartz substrate, the bond strength can be enhanced by a heat treatment. When the linear expansion coefficients in the X-direction (SAW propagation direction) of the LT or LN and in the Y-direction different from the X-direction by 90 degrees are significantly different from those of the quartz substrate, the heat treatment after the bonding process may cause damage to the substrate. When the difference between the expansion coefficients in the X-direction and the Y-direction is greater, damage during the heat treatment is more likely to occur. Therefore, selecting orientations of the layers being bonded may reduce the expansion coefficient difference between the layers. It is noted that even within the same layer, expansion coefficient difference between the X-direction and the Y-direction may be reduced.

[0088] It is noted that in some embodiments, in terms of one or more performance properties, a combination of the bonding layers having orientation angles other than the orientation angles for addressing the above-identified problems may be sometimes desired.

[0089] It is noted that in some embodiments, a directly bonding technique can be difficult to be applied to an oxide substrate such as LT and quartz. On the other hand, an LT or LN layer and a silicon (Si) layer can be directly bonded to each other and the bonding is sufficiently strong to dispense with the heat treatment. Thus, in some embodiments, after bonding the LT or LN layer to the Si layer by such a directly bonding technique, the LT or LN can be thinned to a desired thickness. Then, a polished surface of the thinned LT or LN plate can be bonded to a quartz substrate, and the Si layer can be etched to realize an assembly of LT, LN thin plate/quartz substrate. Because no polishing process is performed after the above-described processes, mechanical problem associated with polishing is not likely to occur in the manufacturing process even if the bond strength is weak to some extent.

[0090] As described above, Figure 1 shows a conventional structure of a surface acoustic wave (SAW) resonator 10 including an interdigital transducer (IDT) electrode 12 formed on an LT or LN 18 and reflectors 14, 16 formed on both sides of the IDT electrode 12. Figure 2 shows an example structure of an SAW resonator 100 including a combination of an LT thin plate or an LN thin plate 104 with a quartz substrate 112. An IDT electrode 102 is shown to be

formed on a surface 110 of the LT or LN thin plate 104, and reflectors 114, 116 are shown to be formed on both sides of the IDT electrode 102.

[0091] As mentioned above, Figure 4 shows an impedance characteristic plot as a function of frequency for the SAW resonator 10 of Figure 1, and Figure 5 shows an impedance characteristic plot as a function of frequency for the SAW resonator 100 of Figure 2. In the example of Figure 4, the IDT electrode (12 in Figure 1) is a copper (Cu) electrode formed in a direction of the SAW propagating in the X-direction (referred to as – plane of 42°YXLT ((0°, 312°, 0°) plane in Euler angle)) on a – plane of 42°-rotated Y-plate LT substrate. In the drawing, a point where the impedance is minimum is referred to as a resonant impedance Z_r , its corresponding frequency is referred to as a resonant frequency f_r , a point where the impedance is maximum is referred to as an antiresonant impedance Z_a , and its corresponding frequency is referred to as an antiresonant frequency f_a . The bandwidth is represented as $(f_a - f_r)/f_r$ and the impedance ratio is represented as $20 \cdot \log(Z_a/Z_r)$.

[0092] As also mentioned above, Figure 5 shows an actual measurement characteristic of an SAW resonator manufactured by combining a 42°YXLT (IDT formed on +plane of 42°YXLT, (0°, 132°, 0°) plane in Euler angle) thin plate with a 42°45'Y90°X quartz substrate (propagating in a direction offset by 90° from the X-axis: (0°, 132°45', 90°) in Euler angle). Combining the LT and the quartz may allow the bandwidth to be broader from 4.2% to 5.1% and the impedance ratio to be greater from 51dB to 80dB resulting in an improvement of as much as 29dB. Therefore, combining the LT with the quartz substrate may significantly improve the frequency characteristic.

[0093] It is noted that a piezoelectric body has a polarity of plus (+) and minus (-) with respect to the c-axis. For example, the surface expressed as 42°-rotated Y-plate, (0°, 132°, 0°) in Euler angle represents the (+) surface and its rear surface, i.e., 180°-rotated (0°, 312°, 0°), represents the (-) surface.

[0094] Figures 6A-6H show that in some embodiments, SAW resonators 100 can have different combinations of polarity orientations of a piezoelectric layer 104 (e.g., LT or LN) and polarity orientations of a substrate 112 (e.g., quartz). In Figures 6A-6H, the piezoelectric layer 104 of each SAW resonator 100 is shown to include a first surface 103a and a second surface 103b, and the substrate 112 of the same SAW resonator is shown to include a

first surface 113a and a second surface 113b. The second surface 103b of the piezoelectric layer 104 is shown to engage the first surface 113a of the substrate 112. Thus, for the purpose of description, the second surface 103b of the piezoelectric layer 104 and the first surface 113a of the substrate 112 can be considered to be engaging surfaces, and the first surface 103a of the piezoelectric layer 104 and the second surface 113b of the substrate 112 can be considered to be non-engaging surfaces.

[0095] Figure 6A shows that in some embodiments, the piezoelectric layer 104 of a SAW resonator 100 can be configured so that its polarity results in the engaging surface 103b being a minus (−) surface, and the substrate 112 of the SAW resonator 100 can be configured so that its polarity results in the engaging surface 113a being a plus (+) surface. In such a configuration, the non-engaging surface 103a of the piezoelectric layer 104 is a plus (+) surface, and the non-engaging surface 113b of the substrate 112 is a plus minus (−) surface. More detailed examples of minus (−) and plus (+) surfaces are described herein in reference to Figures 7 and 8.

[0096] Figure 6B shows that in some embodiments, the piezoelectric layer 104 of a SAW resonator 100 can be configured so that its polarity results in the engaging surface 103b being a minus (−) surface, and the substrate 112 of the SAW resonator 100 can be configured so that its polarity results in the engaging surface 113a being a minus (−) surface. In such a configuration, the non-engaging surface 103a of the piezoelectric layer 104 is a plus (+) surface, and the non-engaging surface 113b of the substrate 112 is a plus (+) surface.

[0097] Figure 6C shows that in some embodiments, the piezoelectric layer 104 of a SAW resonator 100 can be configured so that its polarity results in the engaging surface 103b being a plus (+) surface, and the substrate 112 of the SAW resonator 100 can be configured so that its polarity results in the engaging surface 113a being a plus (+) surface. In such a configuration, the non-engaging surface 103a of the piezoelectric layer 104 is a minus (−) surface, and the non-engaging surface 113b of the substrate 112 is a minus (−) surface.

[0098] Figure 6D shows that in some embodiments, the piezoelectric layer 104 of a SAW resonator 100 can be configured so that its polarity results in the engaging surface 103b being a plus (+) surface, and the substrate 112 of the SAW resonator 100 can be configured so that its polarity results in the engaging

surface 113a being a minus (−) surface. In such a configuration, the non-engaging surface 103a of the piezoelectric layer 104 is a minus (−) surface, and the non-engaging surface 113b of the substrate 112 is a plus (+) surface.

[0099] Figure 6E shows that in some embodiments, the piezoelectric layer 104 of a SAW resonator 100 can be configured so that its polarity results in the engaging surface 103b being a minus (−) surface, and the substrate 112 of the SAW resonator 100 can be configured so that its crystal orientation results in the engaging surface 113a being an unpolarized surface with Euler angles (ϕ , 90° , ψ). In such a configuration, the non-engaging surface 103a of the piezoelectric layer 104 is a plus (+) surface.

[0100] Figure 6F shows that in some embodiments, the piezoelectric layer 104 of a SAW resonator 100 can be configured so that its polarity results in the engaging surface 103b being a minus (−) surface, and the substrate 112 of the SAW resonator 100 can be configured so that its crystal orientation results in the engaging surface 113a being an unpolarized surface with Euler angles (ϕ , -90° , ψ). In such a configuration, the non-engaging surface 103a of the piezoelectric layer 104 is a plus (+) surface.

[0101] Figure 6G shows that in some embodiments, the piezoelectric layer 104 of a SAW resonator 100 can be configured so that its polarity results in the engaging surface 103b being a plus (+) surface, and the substrate 112 of the SAW resonator 100 can be configured so that its crystal orientation results in the engaging surface 113a being an unpolarized surface with Euler angles (ϕ , 90° , ψ). In such a configuration, the non-engaging surface 103a of the piezoelectric layer 104 is a minus (−) surface.

[0102] Figure 6H shows that in some embodiments, the piezoelectric layer 104 of a SAW resonator 100 can be configured so that its polarity results in the engaging surface 103b being a plus (+) surface, and the substrate 112 of the SAW resonator 100 can be configured so that its crystal orientation results in the engaging surface 113a being an unpolarized surface with Euler angles (ϕ , -90° , ψ). In such a configuration, the non-engaging surface 103a of the piezoelectric layer 104 is a minus (−) surface.

[0103] Figures 7A and 7B show a body of material 105 that can be a piezoelectric layer such as an LT or LN layer, or a dielectric layer such as a quartz layer. For the purpose of description, such a body is assumed to have a

planar shape between first and second surfaces 107a, 107b, with a plane parallel to an XY plane of a rectangular coordinate system. In such a configuration, the X direction can be the direction of propagation of a surface acoustic wave.

[0104] In the body 105 of Figures 7A and 7B, polarization can exist or be induced, resulting in a net polarization potential difference between the first and second surfaces 107a, 107b. Such a net polarization difference can result in a net electric charge of one type on the first surface 107a, and a net electric charge of the other type on the second surface 107b.

[0105] For example, and as shown in Figure 7A, when the first surface 107a has a positive (+) polarization potential and the second surface 107b has a negative (−) polarization potential, the first surface 107a has a negative (−) electric charge and the second surface 107n has a positive (+) electric charge. Conversely, and as shown in Figure 7B, when the first surface 107a has a negative (−) polarization potential and the second surface 107b has a positive (+) polarization potential, the first surface 107a has a positive (+) electric charge and the second surface 107n has a negative (−) electric charge.

[0106] For the purpose of description, and unless specified otherwise, a plus (+) surface of the body 105 can correspond to the surface with a positive (+) polarization potential, and a minus (−) surface of the body 105 can correspond to the surface with a negative (−) polarization potential. Accordingly, the plus (+) and minus (−) surfaces of the piezoelectric layer 104 and the substrate 112 of Figures 6A-6D can be understood to follow the foregoing example definition.

[0107] It will be understood that plus (+) and minus (−) surfaces of a body can be defined in other manners. For example, plus (+) and minus (−) surfaces can be defined to correspond to the electric charges of the surfaces. In such a context, a plus (+) surface of a body can correspond to the surface with a positive (+) electrical charge, and a minus (−) surface of the body can correspond to the surface with a negative (−) electrical charge.

[0108] Figure 8A shows an example of a unit cell 117 of a crystal structure of the body 105 of Figures 7A and 7B. Such a unit cell is shown to have a crystal orientation relative to a reference plane 115 that is parallel with the XY plane of the body 105 to provide a negative (−) polarization potential for the corresponding surface of the body 105. Accordingly, such a surface is a minus (−) surface.

[0109] It is noted that, for example, an LT crystal having a 42°Y configuration (42°YLT) can represent a plus (+) ($(0^\circ, 132^\circ, 0^\circ)$ in Euler angle) or minus (−) ($(0^\circ, 312^\circ, 0^\circ)$ in Euler angle) plane. When using only a normal LT or LN, both of such Euler angle configurations ($(0^\circ, 132^\circ, 0^\circ)$ and $(0^\circ, 312^\circ, 0^\circ)$) provide similar frequency characteristics as described herein (e.g., in reference to Figures 10A and 10B). However, it is easier and faster to polish a $(0^\circ, 312^\circ, 0^\circ)$ plane when compared to a $(0^\circ, 132^\circ, 0^\circ)$ plane. Accordingly, in some embodiments, a plane utilized for the example 42°YX LT is a $(0^\circ, 312^\circ, 0^\circ)$ plane.

[0110] Figure 8B shows another example of a unit cell 117 of a crystal structure of the body 105 of Figures 7A and 7B. Such a unit cell is shown to have a crystal orientation relative to a reference plane 115 that is parallel with the XY plane of the body 105 to provide a positive (+) polarization potential for the corresponding surface of the body 105. Accordingly, such a surface is a plus (+) surface.

[0111] By way of an example, an LT crystal having the foregoing plus (+) surface includes Euler angles $(0^\circ, 132^\circ, 0^\circ)$. Thus, a minus (−) surface corresponding to a negative (−) polarization potential surface for a 42°YX configuration (42°YXLT) can be expressed as having Euler angles $(0^\circ, 312^\circ, 0^\circ)$. As described in reference to Figure 8A, use of such a surface (with Euler angles $(0^\circ, 312^\circ, 0^\circ)$) can be preferred in some embodiments.

[0112] For the purpose of description, and referring to Figures 6 and 7, Euler angles defined for a positive (+) polarization potential surface include $(0^\circ, 90^\circ < \theta < 270^\circ, 0^\circ)$. Further, Euler angles defined for a negative (−) polarization potential surface include $(0^\circ, -90^\circ < \theta < 90^\circ, 0^\circ)$. Accordingly, if plus (+) and minus (−) surfaces follow the positive (+) and negative (−) polarization potential surfaces, Euler angles defined for a plus (+) surface include $(0^\circ, 90^\circ < \theta < 270^\circ, 0^\circ)$, and Euler angles defined for a minus (−) surface include $(0^\circ, -90^\circ < \theta < 90^\circ, 0^\circ)$.

[0113] For the purpose of description, it will be understood that an angle α can be expressed in equivalent forms as $\alpha \pm n360^\circ$, where n is an integer. For example, Euler angles $(0^\circ, 90^\circ < \theta < 270^\circ, 0^\circ)$ will be understood to

be equivalent to $(0^\circ, -270^\circ < \theta < -90^\circ, 0^\circ)$. In another example, Euler angles $(0^\circ, -90^\circ < \theta < 90^\circ, 0^\circ)$ will be understood to be equivalent to $(0^\circ, 270^\circ < \theta < 450^\circ, 0^\circ)$.

[0114] In the context of the foregoing example definition of plus (+) and minus (−) surfaces, Table 1 summarizes the SAW resonator configurations of Figures 6A-6D, with an assumption that the piezoelectric layer 104 is LT and the substrate 112 is quartz, and with an understanding that the Euler angles correspond to the upper surface (103a for the LT layer 104, and 113a for the quartz layer 112) of the corresponding layer when viewed as depicted.

Table 1

Figure	Surface combination	Combination of Euler angles
6A	+LT−/+quartz−	$(0^\circ, 90^\circ < \theta < 270^\circ, 0^\circ)$ LT / $(\phi, 90^\circ < \theta < 270^\circ, \psi)$ quartz
6B	+LT−/−quartz+	$(0^\circ, 90^\circ < \theta < 270^\circ, 0^\circ)$ LT / $(\phi, -90^\circ < \theta < 90^\circ, \psi)$ quartz
6C	−LT+/+quartz−	$(0^\circ, -90^\circ < \theta < 90^\circ, 0^\circ)$ LT / $(\phi, 90^\circ < \theta < 270^\circ, \psi)$ quartz
6D	−LT+/−quartz+	$(0^\circ, -90^\circ < \theta < 90^\circ, 0^\circ)$ LT / $(\phi, -90^\circ < \theta < 90^\circ, \psi)$ quartz

[0115] In the examples of Table 1, each quartz substrate is configured to include plus (+) and minus (−) surfaces corresponding to the respective Euler angles. It is noted that when the polarization plane (e.g., Z plane) of a quartz crystal is perpendicular to the surface of the SAW plane (e.g., $(90^\circ, 90^\circ, 90^\circ)$ or $(90^\circ, -90^\circ, 90^\circ)$ in Euler angles), the corresponding quartz substrate does not have (+) and (−) surfaces associated with the polarization plane. In some embodiments, SAW resonators utilizing such a quartz substrate can be implemented.

[0116] Table 2 summarizes the SAW resonator configurations of Figures 6D-6G, with an assumption that the piezoelectric layer 104 is LT and the substrate 112 is quartz, and with an understanding that the Euler angles correspond to the upper surface (103a for the LT layer 104, and 113a for the quartz layer 112) of the corresponding layer when viewed as depicted.

Table 2

Figure	Surface combination	Combination of Euler angles
6E	+LT−/quartz	$(0^\circ, 90^\circ < \theta < 270^\circ, 0^\circ)$ LT / $(\phi, 90^\circ, \psi)$ quartz
6F	+LT−/quartz	$(0^\circ, 90^\circ < \theta < 270^\circ, 0^\circ)$ LT / $(\phi, -90^\circ, \psi)$ quartz
6G	−LT+/quartz	$(0^\circ, -90^\circ < \theta < 90^\circ, 0^\circ)$ LT / $(\phi, 90^\circ, \psi)$ quartz
6H	−LT+/quartz	$(0^\circ, -90^\circ < \theta < 90^\circ, 0^\circ)$ LT / $(\phi, -90^\circ, \psi)$ quartz

[0117] As described herein in greater detail, it is noted that a SAW resonator having a +LT-/quartz configuration (e.g., Figure 6E or Figure 6F) has a higher impedance ratio when compared a SAW resonator with a -LT+/quartz configuration (e.g., Figure 6G or Figure 6H).

[0118] Measurements of bonding strengths for the surface combinations of LT and quartz listed in Tables 1 and 2 are as follows. For the +LT-/quartz- configuration (Figure 6A), measured bonding strength (2γ) is 2.2 Joul/m². For the +LT-/quartz+ configuration (Figure 6B), measured bonding strength (2γ) is 2.0 Joul/m². For the -LT+/quartz- configuration (Figure 6C), measured bonding strength (2γ) is 1.8 Joul/m². For the -LT+/quartz+ configuration (Figure 6D), measured bonding strength (2γ) is 2.0 Joul/m². For the +LT-/quartz configuration of Figure 6E, measured bonding strength (2γ) is 1.9 Joul/m². For the +LT-/quartz configuration of Figure 6F, measured bonding strength (2γ) is 1.9 Joul/m². For the -LT+/quartz configuration of Figure 6G, measured bonding strength (2γ) is 1.9 Joul/m². For the -LT+/quartz configuration of Figure 6H, measured bonding strength (2γ) is 1.9 Joul/m². It is noted that among the eight configurations listed in Tables 1 and 2, the configuration of Figure 6A (+LT-/quartz-) provides the highest bonding strength ($2\gamma = 2.2$ Joul/m²).

[0119] In the foregoing measurement examples, bonding strength is expressed as 2γ , where γ is a bond strength between two substrates as disclosed in Tong, Q., Goesele, U., and Society, E. (1999) Semiconductor Wafer Bonding: Science and Technology, John Wiley & Sons, Inc., New York. Examples related to bonding strengths in various manufacturing process steps are described herein in greater detail.

[0120] In some embodiments, the angle ϕ in Tables 1 and 2 for quartz substrates can have a value in a range of $0^\circ \leq \phi < 180^\circ$. For example, a quartz substrate can have a configuration where $\phi = 0^\circ$ or $\phi = 90^\circ$. In some embodiments, the angle ψ in Tables 1 and 2 for quartz substrates can have a value in a range of $0^\circ \leq \psi < 180^\circ$. For example, a quartz substrate can have a configuration where $\psi = 0^\circ$ or $\psi = 90^\circ$.

[0121] It will be understood that the surface combinations and Euler angle combinations as defined in Tables 1 and 2 can also apply to other piezoelectric layers (including an LN layer) and/or other substrate layers.

[0122] It will also be understood that a plus (+) surface can also be referred to herein as simply a (+) surface, and a minus (−) surface can also be referred to herein as simply a (−) surface.

[0123] Figures 9A and 9B show characteristics of SAW resonators in which an Aluminum electrode having a wavelength (λ) of $2\mu\text{m}$ and a thickness of 0.08λ is formed on the (+) surface of a 20° -rotated Y-plate X-propagation LT ($(0^\circ, 110^\circ, 0^\circ)$ in Euler angle) and the (−) surface ($(0^\circ, 290^\circ, 0^\circ)$ in Euler angle) respectively. Figures 10A and 10B show characteristics of SAW resonators in which the same electrode is formed on the (+) surface of a 42° -rotated Y-plate X-propagation LT ($(0^\circ, 132^\circ, 0^\circ)$ in Euler angle) and the (−) surface ($(0^\circ, 312^\circ, 0^\circ)$ in Euler angle) respectively. As can be seen from these impedance characteristic plots, even though an electrode is formed on either of the (+) or (−) surface of a normal LT substrate, there is essentially no difference in the bandwidth, impedance ratio, resonant frequency, anti-resonant frequency, spurious mode, and the like among the corresponding SAW resonators.

[0124] Based on the foregoing examples, one can see that there is no difference in impedance characteristics between (+) and (−) surfaces of a normal LT substrate. Accordingly, in general, when a normal LT substrate is utilized, the (+) plane and the (−) plane are not distinguished. However, because the (−) plane is easier to polish, such a surface is typically utilized in a normal LT substrate. For example, a $(0^\circ, 312^\circ, 0^\circ)$ plane is typically utilized in the example case of a normal 42°YX LT.

[0125] Figures 11 to 14 show various examples of characteristics associated with different combinations of LT orientations and quartz orientations. More general forms of such combinations (of piezoelectric layer 104 and substrate layer 112) are shown in Figures 6A-6D.

[0126] By way of an example, (+) and (−) surfaces of a 20° -rotated Y-plate X-propagation LT ($(0^\circ, 110^\circ, 0^\circ)$ and $(0^\circ, 290^\circ, 0^\circ)$ in Euler angle respectively), and (+) and (−) surfaces of a $42^\circ45'$ Y-plate 90°X -propagation quartz ($(0^\circ, 132^\circ45', 90^\circ)$ and $(0^\circ, 312^\circ45', 90^\circ)$) were prepared to form four SAW resonators corresponding to the four combinations as shown in Figures 6A-6D, and their frequency characteristics were obtained. Figures 11A-11D show these characteristics.

[0127] Referring to Figures 6A-6D and Figures 11A-11D, it is noted that the combination of the LT whose electrode-side is the (+) surface and whose surface bonded to the quartz is the (-) surface with the quartz whose bonded surface is the (+) surface (Figure 6A) and the combination of the same LT with the quartz whose bonded surface is the (-) surface (Figure 6B) show essentially the same bandwidth and impedance ratio as shown in Figures 11A and 11B respectively. It is also noted that the combination of the LT whose electrode-side is the (-) surface and whose surface bonded to the quartz is the (+) surface with the quartz whose bonded surface is the (+) surface (Figure 6C) and the combination of the same LT with the quartz whose bonded surface is the (-) surface (Figure 6D) show essentially the same bandwidth and impedance ratio as shown in Figures 11C and 11D respectively. However, the embodiments shown in Figures 11A and 11B indicate that a 13% broader bandwidth and 2dB greater impedance ratio can be obtained when compared to the embodiments shown in Figures 11C and 11D. It is noted that the value of 13% is calculated by $6.2\%/5.5\%$ as indicated in Figures 11A-11D.

[0128] Accordingly, regardless of the (+) surface or the (-) surface of the quartz, the structures of the LT whose bonded surface is a (-) surface as shown in Figures 6A and 6B can result in a better characteristic.

[0129] By way of another example, (+) and (-) surfaces of a 20°-rotated Y-plate X-propagation LT ((0°, 110°, 0°) and (0°, 290°, 0°) in Euler angle respectively), and (+) surface of a rotation 35°Y-plate 90°X-propagation to 60°Y-plate 90°X-propagation quartz ((0°, 125°, 90°) to (0°, 150°, 90°) in Euler angle) and the (-) surface of the same quartz ((0°, 305°, 90°) to (0°, 330°, 90°) in Euler angle) were prepared to form four SAW resonators corresponding to the four combinations as shown in Figures 6A-6D, and their frequency characteristics were obtained. The bandwidths and impedance ratios of the four structural combinations are shown in Figures 12A and 12B as a function of Euler angle θ of the quartz. Throughout the quartz of any Euler angle θ , a broader bandwidth and a greater impedance ratio are obtained from the structures of Figures 6A and 6B than those of Figures 6C and 6D.

[0130] By way of another example, (+) surface of a rotation 10°X-propagation to 50°YX-propagation LT ((0°, 100°, 0°) to (0°, 140°, 0°) in Euler angle) and the (-) surface of the same LT ((0°, 280°, 0°) to (0°, 320°, 0°) in Euler

angle), and (+) and (-) surfaces of a $42^{\circ}45'$ -Y-plate 90° X-propagation quartz ($(0^{\circ}, 132^{\circ}45', 90^{\circ})$ and $(0^{\circ}, 312^{\circ}45', 90^{\circ})$ in Euler angle respectively) were prepared. The frequency characteristics of the SAW resonators were obtained for the four combinations as shown in Figures 6A-6D. The bandwidths and impedance ratios of the four structural combinations are shown in Figures 13A and 13B as a function of Euler angle θ of the LT. For the LT of any Euler angles, broader bandwidths and greater impedance ratios can be obtained from the structures of Figures 6A and 6B than those of Figures 6C and 6D.

[0131] In the various examples of Figures 11-13, the piezoelectric layers are LT layers. Similar results can be obtained if LN is used as piezoelectric layers.

[0132] For example, (+) and (-) surfaces of a 25° -rotated Y-plate X-propagation LN ($(0^{\circ}, 115^{\circ}, 0^{\circ})$ and $(0^{\circ}, 295^{\circ}, 0^{\circ})$ in Euler angle respectively), and (+) surface of a rotation 35° Y-plate 90° X-propagation to 60° Y-plate 90° X-propagation quartz ($(0^{\circ}, 125^{\circ}, 90^{\circ})$ to $(0^{\circ}, 150^{\circ}, 90^{\circ})$ in Euler angle) and the (-) surface of the same quartz ($(0^{\circ}, 305^{\circ}, 90^{\circ})$ to $(0^{\circ}, 330^{\circ}, 90^{\circ})$ in Euler angle respectively) were prepared. The frequency characteristics of the SAW resonators were obtained for the four combinations as shown in Figures 6A-6D. The bandwidths and impedance ratios of the four structural combinations are shown in Figures 14A and 14B as a function of Euler angle θ of the quartz. Throughout the quartz of any Euler angles θ , a broader bandwidth and a greater impedance ratio are obtained from the structures of Figures 6A and 6B than those of Figures 6C and 6D. Other combinations of LN with quartz may also provide results similar to the corresponding combinations of LT with quartz as described herein.

[0133] Based at least in part on the foregoing examples, a combination of an LT or LN plate with a quartz substrate may provide a better characteristic in any orientation angles of the LT, LN or quartz by the structures of Figures 6A and 6B using the LT or LN plate whose surface bonded to the quartz substrate is a (-) surface.

[0134] When the polarization potential plane of a SAW resonator is perpendicular to a quartz surface (e.g., $(90^{\circ}, 90^{\circ}, 90^{\circ})$ or $(90^{\circ}, -90^{\circ}, 90^{\circ})$ plane in Euler angles), its quartz substrate does not have a (+) surface and a (-) surface

with respect to the polarization direction. It is noted that the back side of the example (90°, 90°, 90°) plane is (90°, -90°, 90°) plane.

[0135] In the foregoing configuration of the quartz substrate, and referring to Figures 6E-6H and Table 2, the SAW resonators of Figure 6E (+LT-/(90°, 90°, 90°) quartz) and Figure 6F (+LT-/(90°, -90°, 90°) quartz) provide impedance ratios that are higher than those of the SAW resonators of Figure 6G (-LT+/(90°, 90°, 90°) quartz) and Figure 6H (-LT+/(90°, -90°, 90°) quartz). Accordingly, one can see that selecting a (-) or (+) plane of LT or LN for engagement with a quartz substrate is important for obtaining a high impedance ratio, whether or not the quartz substrate includes its own (-) and (+) plane.

[0136] Figures 15A and 15B show a relationship between a thickness (in terms of wavelength λ) of a +20°YXLT-/42°45'Y90°X quartz structure and (a) a bandwidth and (b) an impedance ratio respectively. One can see that an impedance ratio of 70 dB or higher can be obtained in the LT thickness from 0.004 λ to 1.5 λ , and an impedance ratio of 73 dB or higher can be obtained from 0.006 λ to 1 λ . Accordingly, in order to obtain a greater impedance ratio, the thickness of the LT or LN may be 1.5 λ or less, preferably 1 λ or less.

[0137] It will be understood that one or more features of the present disclosure can be applied not only to an SAW resonator but also any SAW devices formed by combining an LT or LN layer with a quartz substrate.

[0138] Figures 16 and 17 show a θ dependence of a substrate on linear expansion coefficients in the X-direction (SAW propagation direction) and the Y-direction (direction 90-degree angled to the SAW propagation direction) for a (0°, θ , 0°) LT and a (0°, θ , 0°) LN respectively. For both of the LT and the LN, the linear expansion coefficient of the X-direction is greater than that of the Y-direction. For both of the LT and the LN, the difference of the linear expansion coefficients between the X-direction and the Y-direction is greater in the vicinity of $\theta=90^\circ$. It is noted that the linear expansion coefficient associated with (ϕ , θ , ψ) is essentially the same as that of (ϕ , $\theta+180^\circ$, ψ); thus, in the context of linear expansion coefficient, (ϕ , $\theta+180^\circ$, ψ) can be referred to herein as (ϕ , θ , ψ).

[0139] Figures 18, 19 and 20 show a θ dependence of linear expansion coefficients in the X-direction and the Y-direction of a substrate for a (0°, θ , 0°) quartz, a (0°, θ , 45°) quartz, and a (0°, θ , 90°) quartz respectively. As shown in Figure 18 for the (0°, θ , 0°) quartz, the linear expansion coefficient of the X-

direction is greater than that of the Y-direction. However, as shown in Figure 19 for the $(0^\circ, \theta, 45^\circ)$ quartz, the linear expansion coefficients of the both directions are substantially identical, and as shown in Figure 20 for the $(0^\circ, \theta, 90^\circ)$ quartz, the linear expansion coefficient of the Y-direction is greater than that of the X-direction.

[0140] Figures 21, 22 and 23 show a ψ dependence of linear expansion coefficients in the X-direction and the Y-direction of a substrate for a $(0^\circ, 126^\circ, \psi)$ quartz, a $(0^\circ, 132^\circ 45', \psi)$ quartz, and a $(0^\circ, 145^\circ, \psi)$ quartz respectively. For any substrates at $0 \leq \psi < 45^\circ$ and $135^\circ \leq \psi \leq 180^\circ$, the linear expansion coefficient of the X-direction is greater than that of Y-direction; for $\psi = 45^\circ$ and 135° , the linear expansion coefficients of the both directions are substantially identical; and for $45^\circ \leq \psi < 135^\circ$, the linear expansion coefficient of the X-direction is less than that of the Y-direction.

[0141] In some embodiments, $(0^\circ, 280^\circ\text{--}330^\circ, 0^\circ)$ (which provides the same linear expansion coefficient as $(0^\circ, 100^\circ\text{--}150^\circ, 0^\circ)$) can be used for the LT layer in view of a suitable coupling coefficient. Any combinations of these layers with a $(0^\circ, \theta, 0^\circ)$ quartz layer may allow the X-direction linear expansion coefficient to be greater than the Y-direction linear expansion coefficient and thus an expansion due to heat is greater in the X-direction at any orientation angle. Therefore, the LT layer is not likely to suffer from a thermal crack at any orientation angle. The difference of the X-direction linear expansion coefficient between the both layers is approximately 15%; however, if the difference is permitted even in the Y-direction, the Y-direction linear expansion coefficient for the LT orientation angle $(0^\circ, 120^\circ\text{--}150^\circ, 0^\circ)$ may be approximately 7.10×10^{-6} to 13.10×10^{-6} , whereas the Y-direction linear expansion coefficient for the quartz orientation angles $(0^\circ, 10^\circ\text{--}80^\circ, 0^\circ)$ and $(0^\circ, 100^\circ\text{--}170^\circ, 0^\circ)$ is approximately 7.48×10^{-6} to 13.52×10^{-6} . Accordingly, the quartz orientation angle may allow the linear expansion coefficients of the both layers to be substantially identical.

[0142] In some embodiments, $(0^\circ, 265^\circ\text{--}336^\circ, 0^\circ)$ (which provides the same linear expansion coefficient as $(0^\circ, 85^\circ\text{--}156^\circ, 0^\circ)$) can be used for the LN, and its combination with the $(0^\circ, \theta, 0^\circ)$ quartz may allow the X-direction linear expansion coefficient to be greater than the Y-direction linear expansion coefficient for the both layers such that a heat expansion in the X-direction can be greater at any orientation angle. The Y-direction linear expansion coefficient of

the LN orientation angle (0° , 85° - 156° , 0°) (which is equivalent to (0° , 265° - 336° , 0°) in terms of linear expansion coefficient) is approximately 7.5×10^{-6} to 14.00×10^{-6} , whereas the Y-direction linear expansion coefficient of the quartz (0° , 5° - 85° , 0°) and (0° , 95° - 175° , 0°) is approximately 7.48×10^{-6} to 13.71×10^{-6} . Accordingly, the linear expansion coefficients of the LN and the quartz can be substantially identical for the orientation angle.

[0143] The magnitude relationship of the X-direction and Y-direction linear expansion coefficients is reversed between the (0° , θ , 0°) LT shown in Figure 16 and the (0° , θ , 90°) quartz shown in Figure 20, and thus a bonding condition of the LT and the quartz may be difficult to find. However, it may be preferable to use an orientation allowing the difference between the expansion coefficient of the (0° , 280° - 330° , 0°) LT, which is a commonly used orientation by itself, and that of the quartz to be as small as possible. Such an orientation (0° , 280° - 330° , 0°) LT has an X-direction linear expansion coefficient of approximately 16.1×10^{-6} , and its $\pm 40\%$ linear expansion coefficient ranges from approximately 9.66×10^{-6} to 22.96×10^{-6} ; and thus the quartz orientation angle that allows the X-direction linear expansion coefficient of the quartz to be within the range may be (0° , 0° - 54° , 90°) and (0° , 126° - 180° , 90°). On the other hand, for the Y-direction, the linear expansion coefficient of the above-described orientation LT ranges from approximately 4.46×10^{-6} to 13.1×10^{-6} , and its $\pm 40\%$ linear expansion coefficient ranges from approximately 6.24×10^{-6} to 18.34×10^{-6} ; and thus the quartz orientation angle to satisfy these coefficients may be (0° , 0° - 180° , 90°). To that end, for the example orientation (0° , 100° - 150° , 0°) LT, a quartz orientation angle that allows the linear expansion coefficient difference between the LT and the quartz in the X-direction and the Y-direction to be within $\pm 40\%$ may be (0° , 0° - 54° , 90°) and (0° , 126° - 180° , 90°).

[0144] The magnitude relationship of the X-direction and Y-direction linear expansion coefficients are reversed between the (0° , θ , 0°) LN shown in Figure 17 and the (0° , θ , 90°) quartz shown in Figure 20; however, it may be preferable to use an orientation allowing the difference between the expansion coefficient of the (0° , 85° - 156° , 0°) LN, which is commonly used orientation by itself, and that of the quartz to be as small as possible. As shown in Figure 17, the X-direction linear expansion coefficient of the (0° , 85° - 156° , 0°) LN is approximately 15.4×10^{-6} , and its $\pm 40\%$ X-direction linear expansion coefficient

is approximately 9.24×10^{-6} to 21.56×10^{-6} . Accordingly, the quartz corresponding to the coefficients has orientations of $(0^\circ, 0^\circ-58^\circ, 90^\circ)$ and $(0^\circ, 122^\circ-180^\circ, 90^\circ)$ as derived from Figure 20. On the other hand, the Y-direction linear expansion coefficient of the same orientation LN ranges from approximately 7.62×10^{-6} to 14.08×10^{-6} , the Y-direction linear expansion coefficient of the $(0^\circ, 0^\circ-180^\circ, 90^\circ)$ quartz is approximately 13.71×10^{-6} , and the linear expansion coefficient of any orientations can be approximate to that of the above-described orientation LN. Therefore, the quartz orientation satisfying the difference of linear expansion coefficients between the $(0^\circ, 85^\circ-156^\circ, 0^\circ)$ LN and the $(0^\circ, \theta, 90^\circ)$ quartz in the X-direction and the Y-direction within $\pm 40\%$ can be $(0^\circ, 0^\circ-58^\circ, 90^\circ)$ and $(0^\circ, 122^\circ-180^\circ, 90^\circ)$.

[0145] Referring to Figures 21, 22 and 23, the X-direction and Y-direction linear expansion coefficients of the $(0^\circ, \theta, \psi)$ quartz are substantially identical when $\psi=45^\circ$ and 135° , whereas the linear expansion coefficient of the X-direction is greater than that of Y-direction when $0 \leq \psi < 45^\circ$ and $135^\circ \leq \psi \leq 180^\circ$. The same applies to other θ . Therefore, the $(0^\circ, 0^\circ-180^\circ, 0^\circ-45^\circ)$ and $(0^\circ, 0^\circ-180^\circ, 135^\circ-180^\circ)$ quartz has a linear expansion coefficient of the X-direction greater than that of the Y-direction similar to the above-described LT and LN, and thus a desirable orientation angle for bonding. Further, as shown in Figures 21, 22 and 23, the X-direction and Y-direction linear expansion coefficients at $\psi=30^\circ$ to 45° is within $\pm 7\%$ with respect to the X-direction and Y-direction linear expansion coefficients at $\psi=45^\circ$, and the magnitude relationship of the X-direction and Y-direction linear expansion coefficients is reversed between $\psi=30^\circ$ to 45° and $\psi=45^\circ$ to 60° ; however, still be within $\pm 7\%$ and a sufficient bond strength can be obtained even in the $(0^\circ, 0^\circ-180^\circ, 30^\circ-60^\circ)$ quartz. Similarly, the X-direction and Y-direction linear expansion coefficients at $\psi=120^\circ$ to 150° is also within $\pm 7\%$ with respect to the X-direction and Y-direction linear expansion coefficients at $\psi=135^\circ$, and thus a sufficient bond strength can be obtained even in the $(0^\circ, 0^\circ-180^\circ, 120^\circ-150^\circ)$ quartz. Therefore, the $(0^\circ, 0^\circ-180^\circ, 30^\circ-60^\circ)$ quartz and the $(0^\circ, 0^\circ-180^\circ, 120^\circ-150^\circ)$ quartz have an orientation angle suitable for bonding to the LT or LN, and preferably, the $(0^\circ, 0^\circ-180^\circ, 0^\circ-45^\circ)$ and $(0^\circ, 0^\circ-180^\circ, 135^\circ-180^\circ)$ quartz is a more suitable orientation angle.

[0146] Figures 24A-24C show an example process that can be utilized to manufacture a SAW resonator having one or more features as described

herein. Figures 25A-25E show another example process that can be utilized to manufacture a SAW resonator having one or more features as described herein. In both examples, an LT material is utilized as a piezoelectric; however, it will be understood that other materials, including an LN material, may be utilized.

[0147] In the first example, Figure 24A shows that in some embodiments, a manufacturing process can include a process step where an assembly 132 of a relatively thick LT plate 130 and a quartz plate 112 is formed or provided. In some embodiments, the relatively thick LT plate and the quartz plate can be cleaned and activated on their respective mirror surface sides, and the surfaces can be pressed to be bonded. Optionally or alternatively, bonding can be performed by using a thin film made of silicon (Si) and the like between the two plates.

[0148] Figure 24B shows a process step where the thickness of the relatively thick LT plate 130 is reduced to a thinner LT plate 134, so as to form an assembly 136. In some embodiments, such a thinning process step can be achieved by, for example, polishing process such as a mechanical polishing process, a chemical mechanical process, etc. In Figure 24B, the thinner LT plate 134 is shown to include a first surface that engages with the quartz plate 112 (e.g., by bonding), and a second surface, opposite from the first surface, resulting from the thinning process step. In some embodiments, the thinning process step can be performed to provide a desired thickness of the thinner LT plate in a range of, for example, 0.3 to 1 μm .

[0149] Figure 24C shows a process step where an electrode 102 is formed on the second surface of the LT plate 134, so as to form an assembly 138. As described herein, such an electrode can include an interdigitized arrangement of fingers 122a, 122b.

[0150] In some embodiments, some or all of the process steps associated with Figures 24A-24C can be implemented for an individual unit to produce a single unit of the assembly 138, be implemented for a plurality of individual units to produce a plurality of respective single units of assemblies 138, or be implemented while a plurality units are attached in an array format (e.g., wafer format) followed by singulation to produce a plurality of singulated units of assemblies 138.

[0151] In the second example, Figure 25A shows that in some embodiments, a manufacturing process can include a process step where an assembly 142 of a relatively thick LT plate 130 and a handling substrate (e.g., silicon substrate) 140 is formed or provided. In some embodiments, the relatively thick LT plate and the silicon (Si) substrate can be cleaned and activated on their respective mirror surface sides, and the mirror surface sides of the relatively thick LT plate and the Si substrate can be directly bonded while pressed in vacuum.

[0152] Figure 25B shows a process step where the thickness of the relatively thick LT plate 130 is reduced to a thinner LT plate 144, so as to form an assembly 146. In some embodiments, such a thinning process step can be achieved by, for example, polishing process such as a mechanical polishing process, a chemical mechanical process, etc. In Figure 25B, the thinner LT plate 144 is shown to include a first surface resulting from the thinning process step, and a second surface, opposite from the first surface, attached to the handling substrate 140. In some embodiments, the thinning process step can be performed to provide a desired thickness of the thinner LT plate in a range of, for example, 0.3 to 1 μm .

[0153] Figure 25C shows a process step where the first surface of the LT plate 144 is attached to a quartz plate 112, so as to form an assembly 148. In some embodiments, the first surface of the LT plate 144 can be attached (e.g., bonded) directly to the quartz plate 112. In some embodiments, the relatively thick LT plate and the quartz plate can be cleaned and activated on their respective mirror surface sides, and the surfaces can be pressed to be bonded. In some embodiments, the LT plate 144 can be bonded to the quartz plate 112 so as to provide a surface combination as described herein in reference to Tables 1 and 2, such as the surface combination +LT-/ +quartz- or +LT-/ -quartz+, or a surface combination +LT-/quartz.

[0154] Figure 25D shows a process step where the handling substrate (140 in Figure 25C) is removed so as to partially or fully expose the LT plate 144, so as to form an assembly 150. In some embodiments, such removal of the handling substrate (such as a silicon substrate) can be achieved by, for example, an etching process (e.g., plasma etching process). In some embodiments, the LT plate 144 in the assembly 150 of Figure 25D may or may not be substantially the same as the LT plate 144 in the assembly 148 of Figure 25C. For the

purpose of description, it will be understood that the exposed surface resulting from the removal of the handling substrate is similar to the second surface of the LT plate 144 described in reference to Figure 25B.

[0155] Figure 25E shows a process step where an electrode 102 is formed on the second surface of the LT plate 144, so as to form an assembly 152. As described herein, such an electrode can include an interdigitized arrangement of fingers 122a, 122b.

[0156] In some embodiments, some or all of the process steps associated with Figures 25A-25E can be implemented for an individual unit to produce a single unit of the assembly 152, be implemented for a plurality of individual units to produce a plurality of respective single units of assemblies 152, or be implemented while a plurality units are attached in an array format (e.g., wafer format) followed by singulation to produce a plurality of singulated units of assemblies 152.

[0157] It is noted that in the example manufacturing process of Figures 24A-24C, the bond strength between the quartz or glass plate and the LT or LN plate can be relatively weak and, during the polishing process, the LT plate may be peeled, cracked or the like, to be often prevented from being polished to a desired thickness. Figure 26A shows an example of damage after a heat treatment of 20 hours at 200°C for enhancing the bond strength (in Figure 24A). Figure 26B shows an example of an LT partially peeled due to a weak bond strength when the LT is polished to 5 μ m.

[0158] A method for measuring the strength of two bonded substrates and also an equation of a bond strength γ may be found in Tong, Q., Goesele, U., and Society, E. (1999) Semiconductor Wafer Bonding: Science and Technology, John Wiley & Sons, Inc., New York. The bond force between quartz and LT is typically 1 Joul/m² or less in various bonding techniques. Similarly, the bonding force between LT and glass, LN and quartz, or LN and glass is typically 1 Joul/m² or less.

[0159] On the other hand, the bond force between silicon, sapphire and the like other than quartz and LT or LN is as high as 30 Joul/m² or more, regardless of whether or not a heat treatment is performed when or after bonding; and therefore the LT or LN plate likely will not be peeled or cracked even if

polished to 0.3 μ m. Accordingly, the example manufacturing process of Figures 25A-25E can be preferable in many manufacturing applications.

[0160] Referring to Figures 25A-25E, when the mirror surface sides of LT and Si are directly bonded while pressed in vacuum, the bond strength γ was 43 Joul/m². Then, the LT plate can be polished to an example thickness of 0.3 μ m without peeling or damage. An example of a polished LT surface is shown in Figure 27A. Next, the LT polished surface and the quartz surface can be cleaned, activated, and pressed to provide bonding. Subsequently, Si can be etched using, for example, plasma etching. Figure 27B shows a photograph of the resulting assembly (150 in Figure 25D) from the LT side. The bond strength γ between the LT plate and the quartz plate was 0.97 Joul/m², which can provide sufficient strength for further processing to produce a SAW resonator, because no polishing is necessary after the step of bonding LT and quartz.

[0161] The resulting assembly (150 in Figure 25D) can be used and an IDT electrode can be formed on the thinned LT plate to manufacture a SAW resonator having one or more features as described herein.

[0162] In some embodiments, and as described herein in reference to Figures 6A-6H and Tables 1 and 2, bonding strength between LT and quartz can vary depending on crystal orientations of LT and/or quartz. For example, it is noted that among the eight configurations listed in Tables 1 and 2, the configuration of Figure 6A (+LT-/ +quartz-) provides the highest bonding strength ($2\gamma = 2.2$ Joul/m², or $\gamma = 1.1$ Joul/m²).

[0163] Accordingly, it will be understood that in some embodiments, the example process of Figures 24A-24C can be implemented with, for example, +LT-/ +quartz- (Figure 6A) or +LT-/ -quartz+ (Figure 6B) when a higher bonding strength between LT and quartz is desired. Preferably, the +LT-/ +quartz- configuration of Figure 6A can be utilized if the highest bonding strength between LT and quartz is desired.

[0164] It will also be understood that in some embodiments, the example process of Figures 25A-25E can also be implemented with, for example, +LT-/ +quartz- (Figure 6A) or +LT-/ -quartz+ (Figure 6B) when a higher bonding strength between LT and quartz is desired. Preferably, the +LT-/ +quartz- configuration of Figure 6A can be utilized if the highest bonding strength between LT and quartz is desired. However, since the example process of Figures 25A-

25E utilizes a handling substrate (such as a silicon substrate) as described herein, it will be understood that in some embodiments, the process of Figures 25A-25E can be implemented with any of the configurations of Figures 6A-6H and Tables 1 and 2.

[0165] An example frequency characteristic of the resulting SAW resonator is shown in Figure 28. An impedance ratio of 82dB, which is greater by 2dB than the example characteristic shown in Figure 5, was obtained. Further, the LT plate having a 0.3 μ m thickness can be used to realize a 2.3GHz high-frequency SAW resonator.

[0166] Accordingly, by utilizing the technique described in reference to Figures 25A-25E, a piezoelectric plate such as LT or LN plate can be polished to approximately 0.3 μ m such that a SAW device of 2GHz or greater having high Q, high impedance, and better temperature characteristic can be realized. Further, in some embodiments, a bond film may be provided between the piezoelectric thin plate and the quartz. Examples of such a configuration can be found in International Publication No. WO2018/097016 which is expressly incorporated by reference in its entirety.

[0167] Figure 29 shows that in some embodiments, multiple units of SAW resonators can be fabricated while in an array form. For example, a wafer 200 can include an array of units 100', and such units can be processed through a number of process steps while joined together. For example, in some embodiments, all of the process steps of Figures 24A-24C can be achieved while an array of such units are joined together as a wafer having different layers (e.g., quartz layer 112 and LT layer 130, 134). In another example, all of the process steps of Figures 25A-25E can be achieved while an array of such units are joined together as a wafer having different layers (e.g., handle layer 140, LT layer 130, 144 and quartz layer 112).

[0168] Upon completion of process steps in the foregoing wafer format, the array of units 100' can be singulated to provide multiple SAW resonators 100. Figure 29 depicts one of such SAW resonators 100. In the example of Figure 29, the singulated SAW resonator 100 is shown to include an electrode 102 formed on a piezoelectric layer 104 such as an LT or LN layer. Such an piezoelectric layer and the corresponding quartz layer can be configured as described herein to provide desirable features. It will be understood that in some embodiments,

another electrode can be provided, as well as one or more reflectors, on the piezoelectric layer.

[0169] Figure 30 shows that in some embodiments, a SAW resonator 100 having or more features as described herein can be implemented as a part of a packaged device 300. Such a packaged device can include a packaging substrate 302 configured to receive and support one or more components, including the SAW resonator 100.

[0170] Figure 31 shows that in some embodiments, the SAW resonator based packaged device 300 of Figure 30 can be a packaged filter device 300. Such a filter device can include a packaging substrate 302 suitable for receiving and supporting a SAW resonator 100 configured to provide a filtering functionality such as RF filtering functionality.

[0171] Figure 32 shows that in some embodiments, a radio-frequency (RF) module 400 can include an assembly 406 of one or more RF filters. Such filter(s) can be SAW resonator based filter(s) 100, packaged filter(s) 300, or some combination thereof. In some embodiments, the RF module 400 of Figure 32 can also include, for example, an RF integrated circuit (RFIC) 404, and an antenna switch module (ASM) 408. Such a module can be, for example, a front-end module configured to support wireless operations. In some embodiments, some of all of the foregoing components can be mounted on and supported by a packaging substrate 402.

[0172] In some implementations, a device and/or a circuit having one or more features described herein can be included in an RF device such as a wireless device. Such a device and/or a circuit can be implemented directly in the wireless device, in a modular form as described herein, or in some combination thereof. In some embodiments, such a wireless device can include, for example, a cellular phone, a smart-phone, a hand-held wireless device with or without phone functionality, a wireless tablet, etc.

[0173] Figure 33 depicts an example wireless device 500 having one or more advantageous features described herein. In the context of a module having one or more features as described herein, such a module can be generally depicted by a dashed box 400, and can be implemented as, for example, a front-end module (FEM). In such an example, one or more SAW filters as described

herein can be included in, for example, an assembly of filters such as duplexers 526.

[0174] Referring to Figure 33, power amplifiers (PAs) 520 can receive their respective RF signals from a transceiver 510 that can be configured and operated in known manners to generate RF signals to be amplified and transmitted, and to process received signals. The transceiver 510 is shown to interact with a baseband sub-system 408 that is configured to provide conversion between data and/or voice signals suitable for a user and RF signals suitable for the transceiver 510. The transceiver 510 can also be in communication with a power management component 506 that is configured to manage power for the operation of the wireless device 500. Such power management can also control operations of the baseband sub-system 508 and the module 400.

[0175] The baseband sub-system 508 is shown to be connected to a user interface 502 to facilitate various input and output of voice and/or data provided to and received from the user. The baseband sub-system 508 can also be connected to a memory 504 that is configured to store data and/or instructions to facilitate the operation of the wireless device, and/or to provide storage of information for the user.

[0176] In the example wireless device 500, outputs of the PAs 520 are shown to be routed to their respective duplexers 526. Such amplified and filtered signals can be routed to an antenna 516 through an antenna switch 514 for transmission. In some embodiments, the duplexers 526 can allow transmit and receive operations to be performed simultaneously using a common antenna (e.g., 516). In Figure 33, received signals are shown to be routed to "Rx" paths (not shown) that can include, for example, a low-noise amplifier (LNA).

[0177] Unless the context clearly requires otherwise, throughout the description and the claims, the words "comprise," "comprising," and the like are to be construed in an inclusive sense, as opposed to an exclusive or exhaustive sense; that is to say, in the sense of "including, but not limited to." The word "coupled", as generally used herein, refers to two or more elements that may be either directly connected, or connected by way of one or more intermediate elements. Additionally, the words "herein," "above," "below," and words of similar import, when used in this application, shall refer to this application as a whole and

not to any particular portions of this application. Where the context permits, words in the above Description using the singular or plural number may also include the plural or singular number respectively. The word “or” in reference to a list of two or more items, that word covers all of the following interpretations of the word: any of the items in the list, all of the items in the list, and any combination of the items in the list.

[0178] The above description of embodiments of the invention is not intended to be exhaustive or to limit the invention to the precise form disclosed above. While specific embodiments of, and examples for, the invention are described above for illustrative purposes, various equivalent modifications are possible within the scope of the invention, as those skilled in the relevant art will recognize. For example, while processes or blocks are presented in a given order, alternative embodiments may perform routines having steps, or employ systems having blocks, in a different order, and some processes or blocks may be deleted, moved, added, subdivided, combined, and/or modified. Each of these processes or blocks may be implemented in a variety of different ways. Also, while processes or blocks are at times shown as being performed in series, these processes or blocks may instead be performed in parallel, or may be performed at different times.

[0179] The teachings of the invention provided herein can be applied to other systems, not necessarily the system described above. The elements and acts of the various embodiments described above can be combined to provide further embodiments.

[0180] While some embodiments of the inventions have been described, these embodiments have been presented by way of example only, and are not intended to limit the scope of the disclosure. Indeed, the novel methods and systems described herein may be embodied in a variety of other forms; furthermore, various omissions, substitutions and changes in the form of the methods and systems described herein may be made without departing from the spirit of the disclosure. Claims and their equivalents are intended to cover such forms or modifications as would fall within the scope and spirit of the disclosure.

WHAT IS CLAIMED IS:

1. An acoustic wave device comprising:
a quartz substrate including a first surface;
a piezoelectric plate formed from LiTaO_3 or LiNbO_3 and including a first surface configured to support a surface acoustic wave and a second surface in engagement with the first surface of the quartz substrate, the second surface being a minus surface resulting from crystal structure orientation of the piezoelectric plate; and
an interdigital transducer electrode formed on the first surface of the piezoelectric plate and configured to provide transducer functionality associated with the surface acoustic wave.
2. The acoustic wave device of claim 1 wherein the crystal structure orientation of the piezoelectric plate includes Euler angles (0° , $90^\circ < \theta < 270^\circ$, 0°).
3. The acoustic wave device of claim 2 wherein the first surface of the quartz substrate is a plus surface resulting from crystal structure orientation of the quartz substrate.
4. The acoustic wave device of claim 3 wherein the crystal structure orientation of the quartz substrate includes Euler angles (ϕ , $90^\circ < \theta < 270^\circ$, ψ), the angle ϕ having a value in a range of $0^\circ \leq \phi < 180^\circ$, the angle ψ having a value in a range of $0^\circ \leq \psi < 180^\circ$.
5. The acoustic wave device of claim 4 wherein the angle ϕ has a value of 0° .
6. The acoustic wave device of claim 4 wherein the angle ψ has a value of 0° .

7. The acoustic wave device of claim 2 wherein the first surface of the quartz substrate is a minus surface resulting from crystal structure orientation of the quartz substrate.

8. The acoustic wave device of claim 7 wherein the crystal structure orientation of the quartz substrate includes Euler angles (ϕ , $-90^\circ < \theta < 90^\circ$, ψ), the angle ϕ having a value in a range of $0^\circ \leq \phi < 180^\circ$, the angle ψ having a value in a range of $0^\circ \leq \psi < 180^\circ$.

9. The acoustic wave device of claim 8 wherein the angle ϕ has a value of 0° .

10. The acoustic wave device of claim 8 wherein the angle ψ has a value of 0° .

11. The acoustic wave device of claim 2 wherein the first surface of the quartz substrate is an unpolarized surface resulting from crystal structure orientation of the quartz substrate.

12. The acoustic wave device of claim 11 wherein the crystal structure orientation of the quartz substrate includes Euler angles (ϕ , 90° , ψ) or (ϕ , -90° , ψ), the angle ϕ having a value in a range of $0^\circ \leq \phi < 180^\circ$, the angle ψ having a value in a range of $0^\circ \leq \psi < 180^\circ$.

13. The acoustic wave device of claim 12 wherein the angle ϕ has a value of 90° and the angle ψ has a value of 90° .

14. The acoustic wave device of claim 1 wherein the piezoelectric plate is formed from LiTaO_3 and the quartz substrate includes Euler angles (0° , 10° - 80° , 0°), (0° , 100° - 170° , 0°), (0° , 190° - 260° , 0°) or (0° , 280° - 350° , 0°).

15. The acoustic wave device of claim 1 wherein the piezoelectric plate is formed from LiNbO_3 and the quartz substrate includes Euler angles (0° , 5° - 85° , 0°), (0° , 95° - 175° , 0°), (0° , 185° - 265° , 0°) or (0° , 275° - 355° , 0°).

16. The acoustic wave device of claim 1 wherein the piezoelectric plate is formed from LiTaO_3 and the quartz substrate includes Euler angles $(0^\circ, 5^\circ\text{-}53^\circ, 90^\circ)$, $(0^\circ, 127^\circ\text{-}175^\circ, 90^\circ)$, $(0^\circ, 185^\circ\text{-}233^\circ, 90^\circ)$ or $(0^\circ, 307^\circ\text{-}355^\circ, 90^\circ)$.

17. The acoustic wave device of claim 1 wherein the piezoelectric plate is formed from LiNbO_3 and the quartz substrate includes Euler angles $(0^\circ, 0^\circ\text{-}52^\circ, 90^\circ)$, $(0^\circ, 126^\circ\text{-}180^\circ, 90^\circ)$, $(0^\circ, 180^\circ\text{-}232^\circ, 90^\circ)$ or $(0^\circ, 306^\circ\text{-}360^\circ, 90^\circ)$.

18. The acoustic wave device of claim 1 wherein the piezoelectric plate is formed from LiTaO_3 or LiNbO_3 and the quartz substrate includes Euler angles $(0^\circ, 0^\circ\text{-}360^\circ, 0^\circ\text{-}60^\circ)$ or $(0^\circ, 0^\circ\text{-}360^\circ, 120^\circ\text{-}180^\circ)$.

19. The acoustic wave device of claim 18 wherein the piezoelectric plate is formed from LiTaO_3 or LiNbO_3 and the quartz substrate includes Euler angles $(0^\circ, 0^\circ\text{-}360^\circ, 0^\circ\text{-}45^\circ)$ or $(0^\circ, 0^\circ\text{-}360^\circ, 135^\circ\text{-}180^\circ)$.

20. The acoustic wave device of claim 1 further comprising first and second reflectors implemented on the first surface of the piezoelectric plate and positioned on first and second sides of the interdigital transducer electrode.

21. The acoustic wave device of claim 1 wherein thickness of the piezoelectric plate is in a range of 0.04λ to 1.5λ , the quantity λ being wavelength of the surface acoustic wave.

22. The acoustic wave device of claim 21 wherein the thickness of the piezoelectric plate is in a range of 0.06λ to 1.0λ .

23. A method for fabricating an acoustic wave device, the method comprising:

forming or providing a quartz substrate having a first surface;

forming or providing a piezoelectric plate with LiTaO_3 or LiNbO_3 to include a first surface configured to support a surface acoustic wave and a second surface being a minus surface resulting from crystal structure orientation of the piezoelectric plate; and

coupling the piezoelectric plate with the quartz substrate such that the minus surface of the piezoelectric plate engages the first surface of the quartz substrate.

24. The method of claim 23 further comprising forming an interdigital transducer electrode on the first surface of the piezoelectric plate to provide transducer functionality associated with the surface acoustic wave.

25. The method of claim 23 wherein the crystal structure orientation of the piezoelectric plate includes Euler angles (0° , $90^\circ < \theta < 270^\circ$, 0°).

26. The method of claim 25 wherein the first surface of the quartz substrate is a plus surface, a minus surface or an unpolarized surface resulting from crystal structure orientation of the quartz substrate.

27. The method of claim 26 wherein the first surface of the quartz substrate is a plus surface, and the quartz substrate includes Euler angles (ϕ , $90^\circ < \theta < 270^\circ$, ψ), the angle ϕ having a value in a range of $0^\circ \leq \phi < 180^\circ$, the angle ψ having a value in a range of $0^\circ \leq \psi < 180^\circ$.

28. The method of claim 26 wherein the first surface of the quartz substrate is a minus surface, and the quartz substrate includes Euler angles (ϕ , $-90^\circ < \theta < 90^\circ$, ψ), the angle ϕ having a value in a range of $0^\circ \leq \phi < 180^\circ$, the angle ψ having a value in a range of $0^\circ \leq \psi < 180^\circ$.

29. The method of claim 26 wherein the first surface of the quartz substrate is an unpolarized surface, and the quartz substrate includes Euler

angles $(\varphi, 90^\circ, \psi)$ or $(\varphi, -90^\circ, \psi)$, the angle φ having a value in a range of $0^\circ \leq \varphi < 180^\circ$, the angle ψ having a value in a range of $0^\circ \leq \psi < 180^\circ$.

30. The method of claim 23 wherein the forming or providing of the piezoelectric plate includes forming the piezoelectric plate after the coupling of the piezoelectric plate with the quartz substrate.

31. The method of claim 30 wherein the coupling of the piezoelectric plate with the quartz substrate and the forming of the piezoelectric plate include bonding a thick piezoelectric layer to the quartz substrate, followed by thinning the thick piezoelectric layer to result in the piezoelectric plate engaged to the quartz substrate.

32. The method of claim 31 wherein the thinning of the thick piezoelectric layer includes a polishing process.

33. The method of claim 23 wherein the forming or providing of the piezoelectric plate includes forming the piezoelectric plate before the coupling of the piezoelectric plate with the quartz substrate.

34. The method of claim 33 wherein the coupling of the piezoelectric plate with the quartz substrate and the forming of the piezoelectric plate include attaching a thick piezoelectric layer to a handling substrate, followed by thinning the thick piezoelectric layer to form the minus surface of the piezoelectric plate, followed by bonding the minus surface of the piezoelectric plate to the quartz substrate.

35. The method of claim 34 wherein the coupling of the piezoelectric plate with the quartz substrate and the forming of the piezoelectric plate further include removing the handling substrate to expose the first surface of the piezoelectric plate.

36. The method of claim 35 wherein the handling substrate includes a silicon substrate.

37. The method of claim 35 wherein the attaching of the thick piezoelectric layer to the handling substrate includes bonding the thick piezoelectric layer to the handling substrate.

38. The method of claim 35 wherein the thinning of the thick piezoelectric layer includes a polishing process while the thick piezoelectric layer is attached to the handling substrate.

39. The method of claim 35 wherein the removing of the handling substrate includes an etching process.

40. A radio-frequency filter comprising:
an input node for receiving a signal;
an output node for providing a filtered signal; and
an acoustic wave device implemented to be electrically between the input node and the output node to generate the filtered signal, the acoustic wave device including a quartz substrate with a first surface, and a piezoelectric plate formed from LiTaO_3 or LiNbO_3 and having a first surface configured to support a surface acoustic wave and a second surface in engagement with the first surface of the quartz substrate, the second surface being a minus surface resulting from crystal structure orientation of the piezoelectric plate.

41. The radio-frequency filter of claim 40 further comprising first and second interdigital transducer electrodes formed on the first surface of the piezoelectric plate, the first interdigital transducer electrode electrically connected to the input node and the second interdigital transducer electrode electrically connected to the output node.

42. A radio-frequency module comprising:
- a packaging substrate configured to receive a plurality of components;
 - a radio-frequency circuit implemented on the packaging substrate and configured to support either or both of transmission and reception of signals; and
 - a radio-frequency filter configured to provide filtering for at least some of the signals, and including an acoustic wave device having a quartz substrate with a first surface, and a piezoelectric plate formed from LiTaO_3 or LiNbO_3 and having a first surface configured to support a surface acoustic wave and a second surface in engagement with the first surface of the quartz substrate, the second surface being a minus surface resulting from crystal structure orientation of the piezoelectric plate.
43. A wireless device comprising:
- a transceiver;
 - an antenna; and
 - a wireless system implemented to be electrically between the transceiver and the antenna, the wireless system including a filter configured to provide filtering functionality for the wireless system, the filter including an acoustic wave device having a quartz substrate with a first surface, and a piezoelectric plate formed from LiTaO_3 or LiNbO_3 and having a first surface configured to support a surface acoustic wave and a second surface in engagement with the first surface of the quartz substrate, the second surface being a minus surface resulting from crystal structure orientation of the piezoelectric plate.

44. A method for fabricating an acoustic wave device, the method comprising:

attaching a first surface of a piezoelectric layer to a handling substrate;

performing a thinning operation on the piezoelectric layer to expose a second surface of a reduced-thickness piezoelectric layer attached to the handling substrate;

bonding the second surface of the reduced-thickness piezoelectric layer to a first surface of a permanent substrate; and

removing the handling substrate from the reduced-thickness piezoelectric layer.

45. The method of claim 44 wherein the removing of the handling substrate from the reduced-thickness piezoelectric layer exposes the first surface that was attached to the handling substrate, the first surface configured to support a surface acoustic wave.

46. The method of claim 45 further comprising forming an interdigital transducer electrode on the first surface of the reduced-thickness piezoelectric layer to provide transducer functionality associated with the surface acoustic wave.

47. The method of claim 46 wherein an assembly of the acoustic wave device and the respective interdigital transducer electrode is one of an array of similar assemblies implemented as a wafer.

48. The method of claim 47 further comprising singulating the wafer to provide a plurality of acoustic wave devices.

49. The method of claim 44 wherein the handling substrate includes a silicon substrate.

50. The method of claim 44 wherein the permanent substrate includes a quartz substrate.

51. The method of claim 44 wherein the piezoelectric layer is formed from LiTaO_3 or LiNbO_3 with a crystal structure orientation such that the second surface of the reduced-thickness piezoelectric layer is a minus surface.

52. The method of claim 51 wherein the crystal structure orientation of the piezoelectric plate includes Euler angles (0° , $90^\circ < \theta < 270^\circ$, 0°).

53. The method of claim 52 wherein the first surface of the permanent substrate is a plus surface, a minus surface or an unpolarized surface resulting from crystal structure orientation of the permanent substrate.

54. The method of claim 53 wherein the first surface of the permanent substrate is a plus surface, and the permanent substrate includes Euler angles (ϕ , $90^\circ < \theta < 270^\circ$, ψ), the angle ϕ having a value in a range of $0^\circ \leq \phi < 180^\circ$, the angle ψ having a value in a range of $0^\circ \leq \psi < 180^\circ$.

55. The method of claim 53 wherein the first surface of the permanent substrate is a minus surface, and the permanent substrate includes Euler angles (ϕ , $-90^\circ < \theta < 90^\circ$, ψ), the angle ϕ having a value in a range of $0^\circ \leq \phi < 180^\circ$, the angle ψ having a value in a range of $0^\circ \leq \psi < 180^\circ$.

56. The method of claim 53 wherein the first surface of the permanent substrate is an unpolarized surface, and the permanent substrate includes Euler angles (ϕ , 90° , ψ) or (ϕ , -90° , ψ), the angle ϕ having a value in a range of $0^\circ \leq \phi < 180^\circ$, the angle ψ having a value in a range of $0^\circ \leq \psi < 180^\circ$.

57. A wafer assembly comprising:
a piezoelectric layer having a first surface and a second surface;
a handling substrate attached the first surface of the piezoelectric layer; and
a permanent substrate attached to the second surface of the piezoelectric layer, the handling substrate selected to be removable to expose the first surface of the piezoelectric layer while the piezoelectric layer is attached to the permanent substrate.

58. The wafer assembly of claim 57 wherein the handling substrate is a silicon substrate.

59. The wafer assembly of claim 57 wherein the permanent substrate is a quartz substrate.

60. The wafer assembly of claim 57 wherein the piezoelectric layer is a reduced-thickness piezoelectric layer resulting from a thinning operation on a thick piezoelectric layer having its first surface attached to the handling wafer and without the permanent substrate.

61. The wafer assembly of claim 60 wherein the first surface of the piezoelectric layer is bonded to the handling substrate with a first bond strength, and the second surface of the piezoelectric layer is bonded to the permanent substrate with a second bond strength.

62. The wafer assembly of claim 61 wherein the first bond strength between the piezoelectric layer and the handling substrate is greater than the bond strength between the piezoelectric layer and the permanent substrate, the first bond strength allowing the thinning operation to be performed without damage to the piezoelectric layer.

63. The wafer assembly of claim 62 wherein the first bond strength between the piezoelectric layer and the handling substrate is greater than the

second bond strength between the piezoelectric layer and the permanent substrate by at least an order of magnitude.

64. The wafer assembly of claim 57 wherein the piezoelectric layer is formed from LiTaO_3 or LiNbO_3 with a crystal structure orientation such that the second surface of the reduced-thickness piezoelectric layer is a minus surface.

65. The wafer assembly of claim 64 wherein the crystal structure orientation of the piezoelectric layer includes Euler angles (0° , $90^\circ < \theta < 270^\circ$, 0°).

66. The wafer assembly of claim 65 wherein the first surface of the permanent substrate is a plus surface, a minus surface or an unpolarized surface resulting from crystal structure orientation of the permanent substrate.

67. The wafer assembly of claim 66 wherein the first surface of the permanent substrate is a plus surface, and the permanent substrate includes Euler angles (ϕ , $90^\circ < \theta < 270^\circ$, ψ), the angle ϕ having a value in a range of $0^\circ \leq \phi < 180^\circ$, the angle ψ having a value in a range of $0^\circ \leq \psi < 180^\circ$.

68. The wafer assembly of claim 66 wherein the first surface of the permanent substrate is a minus surface, and the permanent substrate includes Euler angles (ϕ , $-90^\circ < \theta < 90^\circ$, ψ), the angle ϕ having a value in a range of $0^\circ \leq \phi < 180^\circ$, the angle ψ having a value in a range of $0^\circ \leq \psi < 180^\circ$.

69. The wafer assembly of claim 66 wherein the first surface of the permanent substrate is an unpolarized surface, and the permanent substrate includes Euler angles (ϕ , 90° , ψ) or (ϕ , -90° , ψ), the angle ϕ having a value in a range of $0^\circ \leq \phi < 180^\circ$, the angle ψ having a value in a range of $0^\circ \leq \psi < 180^\circ$.