United States Patent Application Publication	20250266807
Kind Code	A1
Publication Date	August 21, 2025
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TRANSVERSELY-EXCITED FILM BULK ACOUSTIC RESONATOR WITH CONTROLLED CONDUCTOR SIDEWALL ANGLES

Abstract

Acoustic resonator devices is provided that includes a piezoelectric layer having a first surface and a second surface; and a first electrode and a second electrode on the first surface of the piezoelectric layer. At least one of the first electrode and second electrode has a side that extends at an angle relative to the first surface of the piezoelectric layer. Moreover, the angle is greater than or equal to 70 degrees and less than 90 degrees. Furthermore, a thickness of the piezoelectric layer is less than a distance between a center of the first electrode and a center of the second electrode.

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Family ID: **1000008589738**

Appl. No.: **19/203651**

Filed: **May 09, 2025**

Related U.S. Application Data

parent US continuation 17975749 20221028 parent-grant-document US 12323130 child US 19203651
parent US continuation PCT/US2021/029649 20210428 PENDING child US 17975749
us-provisional-application US 63017104 20200429
us-provisional-application US 63017501 20200429

Publication Classification

Int. Cl.: **H03H9/17** (20060101); **H03H3/02** (20060101); **H03H9/02** (20060101); **H03H9/13** (20060101); **H03H9/60** (20060101)

U.S. Cl.:

CPC **H03H9/173** (20130101); **H03H3/02** (20130101); **H03H9/02015** (20130101); **H03H9/132** (20130101); **H03H9/174** (20130101); **H03H9/605** (20130101); H03H2003/021 (20130101); H03H2003/023 (20130101)

Background/Summary

CROSS REFERENCE TO RELATED APPLICATIONS [0001] The current application is a continuation of U.S. Ser. No. 17/975,749, filed Oct. 28, 2022, which is a continuation of U.S. International Application No. PCT/US2021/029649, filed Apr. 28, 2021, entitled "Transversely-Excited Film Bulk Acoustic Resonator with Controlled Conductor Side-Wall Angles," which claims priority to U.S. Patent Provisional No. 63/017,104, filed April 29, 2020, and U.S. Patent Provisional No. 63/017,501, also filed Apr. 29, 2020, the contents of each of where are hereby incorporated by reference in their entirety.

TECHNICAL FIELD
[0002] This disclosure relates to radio frequency filters using acoustic wave resonators, and specifically to filters for use in communications equipment.
BACKGROUND
[0003] A radio frequency (RF) filter is a two-port device configured to pass some frequencies and to stop other frequencies, where "pass" means transmit with relatively low signal loss and "stop" means block or substantially attenuate. The range of frequencies passed by a filter is referred to as the "pass-band" of the filter. The range of frequencies stopped by such a filter is referred to as the "stop-band" of the filter. A typical RF filter has at least one pass-band and at least one stop-band. Specific requirements on a pass-band or stop-band depend on the specific application. For example, a "pass-band" may be defined as a frequency range where the insertion loss of a filter is better than a defined value such as 1 dB, 2 dB, or 3 dB. A "stop-band" may be defined as a frequency range where the rejection of a filter is greater than a defined value such as 20 dB, 30 dB, 40 dB, or greater depending on application.
[0004] RF filters are used in communications systems where information is transmitted over wireless links. For example, RF filters may be found in the RF front-ends of cellular base stations, mobile telephone and computing devices, satellite transceivers and ground stations, IoT (Internet of Things) devices, laptop computers and tablets, fixed point radio links, and other communications systems. RF filters are also used in radar and electronic and information warfare systems.
[0005] RF filters typically require many design trade-offs to achieve, for each specific application, the best compromise between performance parameters such as insertion loss, rejection, isolation, power handling, linearity, size and cost. Specific design and manufacturing methods and enhancements can benefit simultaneously one or several of these requirements.
[0006] Performance enhancements to the RF filters in a wireless system can have broad impact to system performance. Improvements in RF filters can be leveraged to provide system performance improvements such as larger cell size, longer battery life, higher data rates, greater network capacity, lower cost, enhanced security, higher reliability, etc. These improvements can be realized at many levels of the wireless system both separately and in combination, for example at the RF module, RF transceiver, mobile or fixed sub-system, or network levels.
[0007] High performance RF filters for present communication systems commonly incorporate

acoustic wave resonators including surface acoustic wave (SAW) resonators, bulk acoustic wave (BA W) resonators, film bulk acoustic wave resonators (FBAR), and other types of acoustic resonators. However, these existing technologies are not well-suited for use at the higher frequencies and bandwidths proposed for future communications networks.

[0008] The desire for wider communication channel bandwidths will inevitably lead to the use of higher frequency communications bands. Radio access technology for mobile telephone networks has been standardized by the 3GPP (3.sup.rd Generation Partnership Project). Radio access technology for 5.sup.th generation mobile networks is defined in the 5G NR (new radio) standard. The 5G NR standard defines several new communications bands. Two of these new communications bands are n77, which uses the frequency range from 3300 MHz to 4200 MHz, and n79, which uses the frequency range from 4400 MHz to 5000 MHz. Both band n77 and band n79 use time-division duplexing (TDD), such that a communications device operating in band n77 and/or band n79 use the same frequencies for both uplink and downlink transmissions. Bandpass filters for bands n77and n79 must be capable of handling the transmit power of the communications device. WiFi bands at 5 GHz and 6GHz also require high frequency and wide bandwidth. The 5G NR standard also defines millimeter wave communication bands with frequencies between 24.25 GHz and 40 GHz.

[0009] The Transversely-Excited Film Bulk Acoustic Resonator (XBAR) is an acoustic resonator structure for use in microwave filters. The XBAR is described in patent U.S. Pat. No. 10,491,291, titled TRANSVERSELY EXCITED FILM BULK ACOUSTIC RESONATOR. An XBAR resonator comprises an interdigital transducer (IDT) formed on a thin floating layer, or diaphragm, of a single-crystal piezoelectric material. The IDT includes a first set of parallel fingers, extending from a first busbar and a second set of parallel fingers extending from a second busbar. The first and second sets of parallel fingers are interleaved. A microwave signal applied to the IDT excites a shear primary acoustic wave in the piezoelectric diaphragm. XBAR resonators provide very high electromechanical coupling and high frequency capability. XBAR resonators may be used in a variety of RF filters including band-reject filters, band-pass filters, duplexers, and multiplexers. XBARs are well suited for use in filters for communications bands with frequencies above 3 GHz.

SUMMARY OF THE INVENTION

[0010] Thus, according to an exemplary aspect, an acoustic resonator device is provided that includes a piezoelectric plate having opposing first and second surfaces; and a first electrode and a second electrode disposed on the first surface of the piezoelectric plate, the first and second electrodes and the piezoelectric plate configured such that a radio frequency signal applied between the first and second electrodes excites a shear primary acoustic mode in the piezoelectric plate. Moreover, the first electrode and the second electrode each have trapezoidal cross-sectional shapes, and a sidewall angle of at least one side surface of the first electrode and a sidewall angle of at least one side surface of the second electrode are greater than or equal to 70 degrees and less than or equal to 110 degrees relative to the first surface of the piezoelectric plate.

[0011] In another exemplary aspect, an acoustic resonator device is provided that includes a piezoelectric plate having opposed first and second surfaces; and an interdigital transducer (IDT) disposed on the first surface of the piezoelectric plate and that includes first and second busbars, a first plurality of IDT fingers extending from the first busbar, and a second plurality of IDT fingers extending from the second busbar and interleaved with the first plurality of fingers. In this exemplary aspect, the first plurality of IDT fingers and the second plurality of IDT fingers have trapezoidal cross-sectional shapes with sidewall angles greater than or equal to 70 degrees and less or equal to 110 degrees relative to the first surface of the piezoelectric plate.

[0012] In yet another exemplary aspect, a method of fabricating an acoustic resonator device is provided that includes depositing a conductor layer on a front surface of a piezoelectric plate having opposed first and second surfaces; and patterning the conductor layer to form interleaved fingers of an interdigital transducer (IDT), the IDT and the piezoelectric plate configured such that a radio frequency signal applied between the first and second busbars excites a shear primary acoustic mode in the piezoelectric plate. In this aspect, patterning the conductor layer comprises controlling sidewall angles of the interleaved fingers such that the interleaved fingers and trapezoidal cross-sectional shapes with sidewall angles greater than or equal to 70 degrees and less than or equal to 110 degrees relative to the first surface of the piezoelectric plate.

Description

DESCRIPTION OF THE DRAWINGS

[0013] FIG. **1** is schematic plan view and two schematic cross-sectional views of a transversely-excited film bulk acoustic resonator (XBAR) according to an exemplary aspect.

[0014] FIG. **2** is an expanded schematic cross-sectional view of a portion of the XBAR of FIG. **1** according to an exemplary aspect.

[0015] FIG. **3** is an alternative schematic cross-sectional view of the XBAR of FIG. **1** according to an exemplary aspect.

[0016] FIG. **4** is a graphic illustrating a shear primary acoustic mode in an XBAR according to an exemplary aspect.

[0017] FIG. **5** is a graph of fractional bandwidth as a function of the ratio of piezoelectric plate thickness to interdigital transducer (IDT) pitch according to an exemplary aspect.

[0018] FIG. **6** is a schematic block diagram of a filter using XBARs according to an exemplary aspect.

[0019] FIG. **7** is a schematic cross-sectional view of two XBARs illustrating a frequency-setting dielectric layer according to an exemplary aspect.

[0020] FIG. **8** is a graph of the impedance of an exemplary XBAR as a function of frequency according to an exemplary aspect.

[0021] FIG. **9** is a graph of the frequency of a spurious mode as a function of sidewall angle according to an exemplary aspect.

[0022] FIG. **10** is a graph identifying preferred combinations of mark and pitch for IDT electrodes with 90° sidewall angles according to an exemplary aspect.

[0023] FIG. **11** is a graph identifying preferred combinations of mark and pitch for IDT electrodes with 85° sidewall angles according to an exemplary aspect.

[0024] FIG. **12** is a graph identifying preferred combinations of mark and pitch for IDT electrodes with 80° sidewall angles according to an exemplary aspect.

[0025] FIG. **13** is a graph identifying preferred combinations of mark and pitch for IDT electrodes with 75° sidewall angles according to an exemplary aspect.

[0026] FIG. **14** is a graph identifying preferred combinations of mark and pitch for IDT electrodes with 70° sidewall angles according to an exemplary aspect.

[0027] FIG. **15** is a graph identifying preferred combinations of mark and pitch for IDT electrodes with 85° to 90° sidewall angles according to an exemplary aspect.

[0028] FIG. **16** is a graph identifying preferred combinations of mark and pitch for IDT electrodes with 80° to 90° sidewall angles according to an exemplary aspect.

[0029] FIG. **17** is a graph identifying preferred combinations of mark and pitch for IDT electrodes with 75° to 90° sidewall angles according to an exemplary aspect.

[0030] FIG. **18** is a graph identifying preferred combinations of mark and pitch for IDT electrodes with 70° to 90° sidewall angles according to an exemplary aspect.

[0031] FIG. **19** is a flow chart of a method of making an XBAR according to an exemplary aspect.

[0032] Throughout this description, elements appearing in figures are assigned three-digit or four-digit reference designators, where the two least significant digits are specific to the element and the one or two most significant digit is the figure number where the element is first introduced. An element that is not described in conjunction with a figure may be presumed to have the same characteristics and function as a previously-described element having the same reference designator.

DETAILED DESCRIPTION

[0033] FIG. **1** shows a simplified schematic top view and orthogonal cross-sectional views of a transversely-excited film bulk acoustic resonator (XBAR) **100**. XBAR resonators such as the resonator **100** may be used in a variety of RF filters including band-reject filters, band-pass filters, duplexers, and multiplexers. XBARs are well suited for use in filters for communications bands with frequencies above 3 GHz.

[0034] In an exemplary aspect, the XBAR **100** comprises a thin film conductor pattern formed on a surface of a piezoelectric plate **110** having a front surface **112** (e.g., a first surface) and a back surface **114** (e.g., a second surface). The first and second surfaces oppose each other and are essentially parallel. For purposes of this disclosure, "essentially parallel" means parallel to the extent possible within normal manufacturing tolerances. The piezoelectric plate is a thin single-crystal layer of a piezoelectric material such as lithium niobate, lithium tantalate, lanthanum gallium silicate, gallium nitride, or aluminum nitride. The piezoelectric plate is cut such that the orientation of the X, Y, and Z crystalline axes with respect to the front and back surfaces is known and consistent. The piezoelectric plate may be, for example, Z-cut, rotated ZY-cut and rotated Y X-cut.

[0035] The back surface **114** of the piezoelectric plate **110** is attached to a surface of the substrate **120** except for a portion of the piezoelectric plate **110** that forms a diaphragm **115** spanning a cavity **140** formed in the substrate **120**. The portion of the piezoelectric plate that spans the cavity is referred to herein as the "diaphragm" due to its physical resemblance to the diaphragm of a microphone. As shown in FIG. **1**, the diaphragm **115** is contiguous with the rest of the piezoelectric plate **110** around all of a perimeter **145** of the cavity **140**. In this context, "contiguous" means "continuously connected without any intervening item".

[0036] The substrate **120** provides mechanical support to the piezoelectric plate **110**. The substrate **120** may be, for example, silicon, sapphire, quartz, or some other material or combination of materials. The back surface **114** of the piezoelectric plate **110** may be attached to the substrate **120** using a wafer bonding process. Alternatively, the piezoelectric plate **110** may be grown on the substrate **120** or otherwise attached to the substrate. The piezoelectric plate **110** may be attached directly to the substrate or may be attached to the substrate **120** via one or more intermediate material layers.

[0037] The cavity **140** is an empty space within a solid body of the resonator **100**. The cavity **140** may be a hole completely through the substrate **120** (as shown in Section A-A and Section B-B) or a recess in the substrate **120**. The cavity **140** may be formed, for example, by selective etching of the substrate **120** before or after the piezoelectric plate **110** and the substrate **120** are attached. In an exemplary aspect, a dielectric layer (e.g., silicon dioxide) can be formed on the substrate **120** with the cavity being formed directly in the dielectric layer.

[0038] The conductor pattern of the XBAR **100** includes an interdigital transducer (IDT) **130**. An IDT is an electrode structure for converting between electrical and acoustic energy in piezoelectric devices. The IDT **130** includes a first plurality of parallel elongated conductors, commonly called "fingers", such as finger **136**, extending from a first busbar **132**. The IDT **130** includes a second plurality of fingers extending from a second busbar **134**. The first and second pluralities of parallel fingers are interleaved. The interleaved fingers overlap for a distance AP, commonly referred to as the "aperture" of the IDT. The center-to-center distance L between the outermost fingers of the IDT **130** is the "length" of the IDT.

[0039] For purposes of this disclosure, the term "busbar" refers to the conductors that interconnect the first and second sets of fingers in an IDT. As shown in FIG. **1**, each busbar **132**, **134** is an elongated rectangular conductor with a long axis orthogonal to the interleaved fingers and having a length approximately equal to the length L of the IDT. The busbars of an IDT need not be rectangular or orthogonal to the interleaved fingers and may have lengths longer than the length of the IDT.

[0040] The first and second busbars **132**, **134** serve as the terminals of the XBAR **100**. A radio frequency or microwave signal applied between the two busbars **132**, **134** of the IDT **130** excites a primary acoustic mode within the piezoelectric plate **110**. As will be discussed in further detail, the primary acoustic mode is a bulk shear mode where acoustic energy propagates along a direction substantially orthogonal to the surface of the piezoelectric plate **110**, which is also normal, or transverse, to the direction of the electric field created by the IDT fingers. Thus, the XBAR is considered a transversely-excited film bulk wave resonator.

[0041] The IDT **130** is positioned on the piezoelectric plate **110** such that at least the fingers of the IDT **130** are disposed on the diaphragm **115** of the piezoelectric plate that spans, or is suspended over, the cavity **140**. As shown in FIG. **1**, the cavity **140** has a rectangular shape with an extent greater than the aperture A P and length L of the IDT **130**. A cavity of an XBAR may have a different shape, such as a regular or irregular polygon. The cavity of an XBAR may more or fewer than four sides, which may be straight or curved.

[0042] For ease of presentation in FIG. **1**, the geometric pitch and width of the IDT fingers is greatly exaggerated with respect to the length (dimension L) and aperture (dimension AP) of the XBAR. An XBAR for a 5G device will have more than ten parallel fingers in the IDT **110**. An XBAR may have dozens, possibly hundreds, of parallel fingers in the IDT **110**. Similarly, the thickness of the piezoelectric plate and IDT fingers are greatly exaggerated in the cross-sectional views.

[0043] FIG. **2** shows a detailed schematic cross-sectional view of the XBAR **100**. The piezoelectric plate **110** is a single-crystal layer of piezoelectrical material having a thickness tp. tp may be, for example, 100 nm to 1500 nm. When used in filters for communications bands from 3.4 GHZ to 6 GHz, the thickness tp may be, for example, 200 nm to 1000 nm.

[0044] The IDT fingers **230**, **235** may be one or more layers of aluminum, a substantially aluminum alloys, copper, a substantially copper alloys, beryllium, gold, molybdenum, or some other conductive material. Thin (relative to the total thickness of the conductors) layers of other metals, such as chromium or titanium, may be formed under and/or over the fingers **230**, **235** to improve adhesion between the fingers and the piezoelectric plate **110** and/or to passivate or encapsulate the fingers. The busbars (**132**, **134** in FIG. **1**) of the IDT may be made of the same or different materials as the fingers.

[0045] For purposes of this disclosure, dimension p is the center-to-center spacing or “pitch” of the IDT fingers, which may be referred to as the pitch of the IDT and/or the pitch of the XBAR. Moreover, dimension m is the width or “mark” of the IDT fingers. The IDT of an XBAR differs substantially from the IDTs used in surface acoustic wave (SAW) resonators. In a SAW resonator, the pitch of the IDT is one-half of the acoustic wavelength at the resonance frequency. Additionally, the mark-to-pitch ratio of a SAW resonator IDT is typically close to 0.5 (i.e., the mark or finger width is about one-fourth of the acoustic wavelength at resonance). In an XBAR, the pitch p of the IDT is typically 2 to 20 times the width m of the fingers. In addition, the pitch p of the IDT is typically 2 to 20 times the thickness tp of the piezoelectric slab **212**. The width of the IDT fingers in an XBAR is not constrained to one-fourth of the acoustic wavelength at resonance. For example, the width of XBAR IDT fingers may be 500 nm or greater, such that the IDT can be fabricated using optical lithography.

[0046] The thickness tm of the IDT fingers **230**, **235** may be from **100** nm to about equal to the width w. The thickness of the busbars (**132**, **134** in FIG. **1**) of the IDT may be the same as, or greater than, the thickness tm of the IDT fingers. For XBARs intended for high power applications, the thickness tm may be greater than 0.85 times the thickness tp of the piezoelectric plate **110**, as described in U.S. Pat. No. 10,637,438.

[0047] As shown in FIG. **2**, the IDT fingers **230**, **235** have trapezoidal (or substantially trapezoidal) cross-sections according to an exemplary aspect. For purposes of this disclosure, the term “substantially trapezoidal” means a generally trapezoidal shape that takes into account minor variations in the structure due to manufacturing variations, for example. Moreover, in the exemplary aspect, the angle between a side of a thin film conductor and the surface on which the conductor is formed is commonly referred to as a “sidewall angle” of the conductor. In FIG. **2**, the angles θ are the sidewall angles of IDT finger **230**. In the exemplary aspect, the sidewall angle is defined as an internal angle within the conductor such that the two sidewall angles of the IDT finger **230** are 80 degrees, although the two sides actually tilt in opposite directions. A conductor with 90-degree sidewall angles has a rectangular cross-section. A conductor with equal sidewall angles other than 90 degrees will have a trapezoidal cross-section. When the sidewall angles are less than 90 degrees, the broader face of the trapezoid will face the surface on which the conductor is formed, as shown in FIG. **2**. When the sidewall angles are greater than 90 degrees, the narrower face of the trapezoid will face the surface on which the conductor is formed (not shown). The two sidewall angles of a conductor are not necessarily equal. When the sidewall angles are not equal, the cross-section of the conductor will be an irregular trapezoid (not shown).
[0048] In FIG. **2**, the IDT fingers **230**, **235** are shown as single layer structures which may be aluminum or some other metal. IDT fingers may include multiple layers of materials. For example, a thin adhesion layer of another material, such as titanium or chrome, may be formed between the IDT fingers **230**, **235** and the piezoelectric plate **110**. When an adhesion layer is present, the sidewall angles of the adhesion layer are not necessarily the same as the sidewall angles θ.
[0049] Here, the IDT finger **230** is an example of “first electrode” and the IDT finger **235** is an example of “second electrode”. As was shown in FIG. **1**, a plurality of first electrodes is connected to the first bus bar **132**. A plurality of second electrodes is connected to the second bus bar **134**. The plurality of first electrodes and the plurality of second electrodes are interleaved.
[0050] FIG. **3** shows a detailed schematic cross-sectional view of a solidly mounted XBAR (SM XBAR) **300**. SM XBARs are first described in patent U.S. Pat. No. 10,601,392, which is herein incorporated by reference. The SM XBAR **300** includes a piezoelectric plate **110** and an IDT (of which only fingers **330** and **335** are visible). The piezoelectric layer **110** has parallel front and back surfaces **112**, **114**. Dimension tp is the thickness of the piezoelectric plate **110**. The width of the IDT fingers **330**, **335** is dimension m, thickness of the IDT fingers is dimension tm, and the IDT pitch is dimension p.
[0051] In contrast to the XBAR devices shown in FIG. **1** and FIG. **2**, the IDT of an SM XBAR is not formed on a diaphragm spanning a cavity in a substrate (**120** in FIG. **1**). Instead, an acoustic Bragg reflector **340** is sandwiched between a surface **322** of a substrate **320** and the back surface **114** of the piezoelectric plate **110**. The term “sandwiched” means the acoustic Bragg reflector **340** is both disposed between and mechanically attached to a surface **322** of the substrate **320** and the back surface **114** of the piezoelectric plate **110**. In some circumstances, thin layers of additional materials may be disposed between the acoustic Bragg reflector **340** and the surface **322** of the substrate **320** and/or between the Bragg reflector **340** and the back surface **114** of the piezoelectric plate **110**. Such additional material layers may be present, for example, to facilitate bonding the piezoelectric plate **110**, the acoustic Bragg reflector **340**, and the substrate **320**.
[0052] The acoustic Bragg reflector **340** includes multiple dielectric layers that alternate between materials having high acoustic impedance and materials have low acoustic impedance. “High” and “low” are relative terms. For each layer, the standard for comparison is the adjacent layers. Each “high” acoustic impedance layer has an acoustic impedance higher than that of both the adjacent low acoustic impedance layers. Each “low” acoustic impedance layer has an acoustic impedance lower than that of both the adjacent high acoustic impedance layers. As will be discussed subsequently, the primary acoustic mode in the piezoelectric plate of an XBAR is a shear bulk wave. Each of the layers of the acoustic Bragg reflector **340** has a thickness equal to, or about, one-

fourth of the wavelength of a shear bulk wave having the same polarization as the primary acoustic mode at or near a resonance frequency of the SM XBAR **300**. Dielectric materials having comparatively low acoustic impedance include silicon dioxide, carbon-containing silicon oxide, and certain plastics such as cross-linked polyphenylene polymers. Materials having comparatively high acoustic impedance include hafnium oxide, silicon nitride, aluminum nitride, silicon carbide, and diamond. All of the high acoustic impedance layers of the acoustic Bragg reflector **340** are not necessarily the same material, and all of the low acoustic impedance layers are not necessarily the same material. In the example of FIG. **3**, the acoustic Bragg reflector **340** has a total of six layers. An acoustic Bragg reflector may have more than, or less than, six layers.

[0053] FIG. **4** is a more detailed graphical illustration of the primary acoustic mode of interest in an XBAR. In particular, FIG. **4** shows a small portion of an XBAR **400** including a piezoelectric plate **410** and three interleaved IDT fingers **430**. A radio frequency (RF) voltage is applied to the interleaved fingers **430**. This voltage creates a time-varying electric field between the fingers. The direction of the electric field is primarily lateral, or parallel to the surface of the piezoelectric plate **410**, as indicated by the arrows labeled “electric field”. Since the dielectric constant of the piezoelectric plate is significantly higher than the surrounding air, the electric field is highly concentrated in the plate relative to the air. The lateral electric field introduces shear deformation, and thus strongly excites a shear-mode acoustic mode, in the piezoelectric plate **410**. Shear deformation is deformation in which parallel planes in a material remain parallel and maintain a constant distance while translating relative to each other. A “shear acoustic mode” is an acoustic vibration mode in a medium that results in shear deformation of the medium. The shear deformations in the XBAR **400** are represented by the curves **460**, with the adjacent small arrows providing a schematic indication of the direction and magnitude of atomic motion. The degree of atomic motion, as well as the thickness of the piezoelectric plate **410**, have been greatly exaggerated for ease of visualization. While the atomic motions are predominantly lateral (i.e. horizontal as shown in FIG. **4**), the direction of acoustic energy flow of the excited primary shear acoustic mode is substantially orthogonal to the surface of the piezoelectric plate, as indicated by the arrow **465**.

[0054] FIG. **5** is a diagram **500** showing a relationship between the structure of an acoustic wave resonators and its fractional bandwidth. Specifically, the solid curve **510** is a plot of the fractional bandwidth of an acoustic wave resonator as a function of tp/p (the ratio of the piezoelectric plate thickness to IDT pitch). As is apparent from FIG. **5**, when tp/p exceeds 0.5, the fractional bandwidth is less than 5% even if tp/p is adjusted. On the other hand, in the case of tp/p≤0.5, if tp/p is changed within this range, a resonator having a high fractional bandwidth ≥5% can be constructed. When tp/p is 0.24 or less, the fractional bandwidth can be increased to 7% or more. In addition, if tp/p is adjusted within this range, a resonator having a higher coupling coefficient can be realized. Therefore, it is understood that a resonator having a high coupling coefficient using a shear bulk mode can be constituted by setting tp/p to 0.24 or less.

[0055] According to an exemplary aspect, the IDT of a resonator has at least one pair of electrodes and may have a large plurality of electrodes. In the case of a single pair of electrodes, p is the distance between the centers of the adjacent electrodes (**230**, **235** in FIG. **2**). In the case of more than two electrodes, p is the average distance between the centers of the adjacent electrodes. When the piezoelectric plate has thickness variation, tp is an average thickness of the piezoelectric layer over the area of the IDT.

[0056] FIG. **6** is a schematic circuit diagram for a high frequency band-pass filter **600** using XBARs. The filter **600** has a conventional ladder filter architecture including three series resonators **610**A, **610**B, **610**C and two shunt resonators **620**A, **620**B. The three series resonators **610**A, **610**B, and **610**C are connected in series between a first port and a second port (hence the term “series resonator”). In FIG. **6**, the first and second ports are labeled “In” and “Out”, respectively. However, the filter **600** is bidirectional and either port may serve as the input or output of the filter. The two shunt resonators **620**A, **620**B are connected from nodes between the series resonators to ground. A filter may contain additional reactive components, such as inductors, not shown in FIG. **6**. All the shunt resonators and series resonators are XBARs. The inclusion of three series and two shunt resonators is exemplary. A filter may have more or fewer than five total resonators, more or fewer than three series resonators, and more or fewer than two shunt resonators. Typically, all of the series resonators are connected in series between an input and an output of the filter. All of the shunt resonators are typically connected between ground and the input, the output, or a node between two series resonators.

[0057] In the exemplary filter **600**, the three series resonators **610**A, B, C and the two shunt resonators **620**A, B of the filter **600** are formed on a single plate **630** of piezoelectric material bonded to a silicon substrate (not visible). Each resonator includes a respective IDT (not shown), with at least the fingers of the IDT disposed over a cavity in the substrate. In this and similar contexts, the term "respective" means "relating things each to each", which is to say with a one-to-one correspondence. In FIG. **6**, the cavities are illustrated schematically as the dashed rectangles (such as the rectangle **635**). In this example, each IDT is disposed over a respective cavity. In other filters, the IDTs of two or more resonators may be disposed over a single cavity.

[0058] Each of the resonators **610**A, **610**B, **610**C, **620**A, **620**B in the filter **600** has resonance where the admittance of the resonator is very high and an anti-resonance where the admittance of the resonator is very low. The resonance and anti-resonance occur at a resonance frequency and an anti-resonance frequency, respectively, which may be the same or different for the various resonators in the filter **600**. In over-simplified terms, each resonator can be considered a short-circuit at its resonance frequency and an open circuit at its anti-resonance frequency. The input-output transfer function will be near zero at the resonance frequencies of the shunt resonators and at the anti-resonance frequencies of the series resonators. In a typical filter, the resonance frequencies of the shunt resonators are positioned below the lower edge of the filter's pass-band and the anti-resonance frequencies of the series resonators are position above the upper edge of the pass-band.

[0059] FIG. **7** is a schematic cross-sectional view through a shunt resonator and a series resonator of a filter **700** that uses a dielectric frequency setting layer to separate the resonance frequencies of shunt and series resonators. As shown, a piezoelectric plate **710** is attached to a substrate **720**. Portions of the piezoelectric plate **710** form diaphragms spanning cavities **740** in the substrate **720**. Interleaved IDT fingers, such as finger **730**, are formed on the diaphragms. A first dielectric layer **750**, having a thickness t**1**, is formed over the IDT of the shunt resonator. The first dielectric layer **750** is considered a "frequency setting layer", which is a layer of dielectric material applied to a first subset of the resonators in a filter to offset the resonance frequencies of the first subset of resonators with respect to the resonance frequencies of resonators that do not receive the dielectric frequency setting layer. The dielectric frequency setting layer is commonly SiO.sub.2 but may be silicon nitride, aluminum oxide, or some other dielectric material. The dielectric frequency setting layer may be a laminate or composite of two or more dielectric materials.

[0060] A second dielectric layer **755**, having a thickness t**2**, may be deposited over both the shunt and series resonator. The second dielectric layer **755** serves to seal and passivate the surface of the filter **700**. The second dielectric layer may be the same material as the first dielectric layer or a different material. The second dielectric layer may be a laminate or composite of two or more different dielectric materials. Further, as will be described subsequently, the thickness of the second dielectric layer may be locally adjusted to fine-tune the frequency of the filter **700**. Thus, the second dielectric layer can be referred to as the "passivation and tuning layer".

[0061] The resonance frequency of an XBAR is roughly proportional to the inverse of the total thickness of the diaphragm including the piezoelectric plate **710** and the dielectric layers **750**, **755**. The diaphragm of the shunt resonator is thicker than the diaphragm of the series resonator by the thickness t**1** of the dielectric frequency setting layer **750**. Thus, the shunt resonator will have a lower resonance frequency than the series resonator. The difference in resonance frequency between series and shunt resonators is determined by the thickness t**1**.

[0062] FIG. **8** is a graph **800** of the magnitude of the impedance versus frequency for two representative XBARs. Specifically, the solid line **810** is a plot of the impedance of a shunt resonator in a ladder filter circuit, such as the ladder filter circuit of FIG. **5**. This resonator has very low impedance at a resonance frequency about 4 GHz and very high impedance at an anti-resonance frequency about 4.5 GHz. The dashed line **920** is a plot of the impedance of a series resonator in the ladder filter circuit. According to the exemplary aspect, this resonator has very low impedance at a resonance frequency about 4.6 GHz and very high impedance at an anti-resonance frequency about 5.2 GHz. Both the shunt resonator and the series resonator shown in FIG. **8** have IDT fingers with trapezoidal cross-sections whose side wall angle θ is set to 70° or more as described below. Both XBARs exhibit spurious resonances at other frequencies.

[0063] Spurious modes located between the resonance frequency of the shunt resonator and the anti-resonance frequency of the series resonator may introduce unacceptable ripples in the filter pass-band. The frequency of spurious modes may be controlled and the amplitude of spurious modes may be suppressed by appropriate selection of the duty factor, or mark/pitch ratio, of the IDT fingers in a range from 0.1 to 0.4.

[0064] The frequency of spurious modes is also affected by the sidewall angle of the IDT fingers. FIG. **9** is a diagram showing the relationship **910** between sidewall angle θ and the frequency of a significant spurious mode (**825** in FIG. **8**) for an exemplary XBAR. The exemplary XBAR includes a 127.5° Y X cut lithium niobate piezoelectric plate with aluminum IDT electrodes. The thickness of the piezoelectric plate and the aluminum electrodes are both 500 nm. The substrate is silicon with a silicon dioxide film 1 um thick between the piezoelectric plate and the substrate. The resonance frequency of the XBAR is about 3880 MHz, as indicated by the dashed line **920**.

[0065] The solid line **910** is a plot of the frequency of the spurious mode as a function of the sidewall angle of the IDT electrodes. When the sidewall angle θ is set to 70° or more, the frequency of the spurious mode is lower than the resonance frequency of 3880 M Hz. A sidewall angle greater than or equal to 70 degrees is particularly beneficial for a shunt resonator in a ladder filter since the spurious mode is at a frequency below the passband of the filter. Reducing the sidewall angle below of 70 degrees causes the spurious mode to move through the resonance frequency.

[0066] The sidewall angle θ may be greater than 90 degrees. However, if the inclination angle θ is too large, problem arise in the manufacturability of the IDT fingers. Therefore, the upper limit of the inclination angle θ may be set to 110° in an exemplary aspect. In addition, m/p (the ratio of IDT finger width to IDT pitch) may be set greater than or equal to 0.12. In such case, resonant characteristic of the resonator may not be degraded.

[0067] U.S. Pat. No. 10,637,438, herein incorporated by reference, describes XBAR resonators for use in high power applications. In such applications, a small amount of power is dissipated in each XBAR due to resistive losses in the IDT fingers and acoustic losses in the IDT fingers and the diaphragm. The primary means of removing heat from the XBAR diaphragm is thermal conduction through the IDT fingers and busbars. To minimize resistive losses and improve heat removal, the IDT conductors are typically as thick or thicker than the diaphragm. For example, an XBAR with a diaphragm thickness of 400 nm may have 500 nm thick conductors.

[0068] Moreover, U.S. Pat. No. 10,637,438 describes the use of a figure of merit (FOM) to define a design space (i.e., combinations of IDT conductor thickness, pitch, and width) that provides XBARs with acceptable performance for use in filters. The FOM is calculated by integrating the negative impact of spurious modes across a defined frequency range. For each combination of IDT conductor thickness and pitch, the FOM is calculated for a range of IDT finger widths. The minimum FOM value over the range of IDT finger widths is considered the minimized FOM for that conductor thickness/pitch combination. The definition of the FOM and the frequency range depend on the requirements of a particular target filter. The frequency range typically includes the pass-band of the target filter and may include one or more stop bands. Spurious modes occurring between the resonance and anti-resonance frequencies of each hypothetical resonator may be accorded a heavier weight in the FOM than spurious modes at frequencies below resonance or above anti-resonance. Hypothetical resonators having a minimized FOM below a threshold value were considered potentially “useable”, which is to say probably having sufficiently low spurious modes for use in the target filter. Hypothetical resonators having a minimized cost function above the threshold value were considered not useable.

[0069] FIG. **10** is a chart **1000** showing combinations of IDT pitch p and IDT finger width or mark m that may provide useable resonators. IDT pitch is normalized to the thickness tp of the piezoelectric plate and the mark m is expressed as a mark-to-pitch ratio m/p. The chart **1000** and all subsequent charts are based on two-dimensional simulations of XBARs with Z-cut lithium niobate diaphragms, aluminum conductors having a thickness 1.25 times the thickness tp of the piezoelectric plate, and no dielectric layers. The chart **1000** is specific to rectangular cross-section IDT fingers with sidewall angle θ=90°. Combinations of IDT pitch and mark falling within unshaded regions, such as region **1010**, are likely to have sufficiently low spurious effects to be useful in a target filter. XBARs with IDT pitch and mark within the intervening shaded regions have unacceptably high spurious modes for use in the target filter. With θ=90°, usable resonators exist for IDT pitch values from about 7.7 tp to over 12.5 tp, Useful resonators do not exist for some pitch values within this range.

[0070] The resonance and anti-resonance frequencies of an XBAR are primarily determined by the thickness of the diaphragm (**115** in FIG. **1**) where the IDT fingers are disposed. The pitch of the IDT has small effect on resonance frequency and the width or mark of the IDT fingers has an even smaller effect on resonance frequency. The pitch and mark of the IDT have much stronger effects on the frequency and amplitude of various spurious modes. Having a range of usable IDT pitch and mark values provides a filter designer with degrees of freedom to, for example, ensure that the spurious modes of different resonators within a filter do not coincide. Additionally, while the pitch of an IDT is set by a photomask and can be reproduced very accurately, the mark of the IDT depends to some extent on process parameters. Thus, a filter design must accommodate some variation in mark due to routine manufacturing tolerances.

[0071] FIG. **11**, FIG. **12**, FIG. **13**, and FIG. **14** are additional charts (**1100**, **1200**, **1300**, **1400** respectively) showing combinations of IDT pitch p and IDT finger width or mark m that may provide useable resonators with sidewall angles of 85°, 80°, 75°, and 70°, respectively. IDT pitch is normalized to the thickness tp of the piezoelectric plate and the mark m is expressed as a mark-to-pitch ratio m/p. In all of these figures, XBARs with IDT pitch and mark-to-pitch ratios within unshaded regions (see, for example regions **1110**, **1210**, **1310**, **1410**) may have sufficiently low spurious effects for use in filters. XBARs with IDT pitch and mark-to-pitch ratios within the intervening shaded regions have unacceptably high spurious modes for use in the target filter.

[0072] Comparison of FIG. **10**, FIG. **11**, FIG. **12**, FIG. **13**, and FIG. **14** shows that useful resonators are available for any specific sidewall angle from 70° to 90°. As sidewall angle θ decreases from 90°, unshaded areas indicating useful resonators shrink slightly and shift towards higher mark-to-pitch ratios. The range of pitch values for useful resonators is about 7.8 tp to 12.5 tp for 85°, 80°, and 75° sidewall angles. With θ=70°, usable resonators exist for IDT pitch values from about 7.9 tp to over 12.3 tp. For any sidewall angle, useful resonators do not exist for some pitch values within the overall range. While the results shown in FIG. **10** through FIG. **14** are specific to a particular structure (piezoelectric material and thickness, electrode thickness, etc.) and FOM algorithm, the general conclusion that useful resonators are available for sidewall angles between 70° and 90° are believed to be valid for other structures and FOM algorithms.

[0073] Since the combinations of IDT pitch and mark that provide useful resonators shift with sidewall angle, it is necessary to control the sidewall angle during production with some tolerance. For example, FIG. **15** is a chart **1500** showing combinations of IDT pitch p and IDT finger mark m that may provide useable resonators with any sidewall angles between 85° and 90°. The unshaded area **1510** identifying useful pitch/mark combinations is significantly smaller than the unshaded areas of FIG. **10** (sidewall angle=90°) or FIG. **11** (sidewall angle=85°).

[0074] FIG. **16**, FIG. **17**, and FIG. **18** are additional charts (**1600**, **1700**, **1800** respectively) showing combinations of IDT pitch p and IDT finger width or mark m that may provide useable resonators with sidewall angles of 80° to 90°, 75° to 90°, and 70° to 90°, respectively. In each case, the unshaded area indicating combinations of IDT pitch p and IDT finger mark m that may provide useable resonators shrinks as the range of possible sidewall angles increases. In particular, the unshaded areas in FIG. **17** and FIG. **18** are very small and may not have sufficient degrees of freedom to design a filter with adequately suppressed spurious modes. It is likely a filter can be designed to accommodate sidewall angles in any 5-degree interval within a range of 70° to 90°, which is equivalent to a manufacturing tolerance of ±2.5 degrees.

[0075] FIG. **19** is a simplified flow chart summarizing a process **1900** for fabricating a filter device incorporating XBARs according to an exemplary aspect. Specifically, the process **1900** is for fabricating a filter device including multiple XBARs, some of which may include a frequency setting dielectric layer. The process **1900** starts at **1905** with a device substrate and a thin plate of piezoelectric material disposed on a sacrificial substrate. The process **1900** ends at **1995** with a completed filter device. The flow chart of FIG. **19** includes only major process steps. Various conventional process steps (e.g. surface preparation, cleaning, inspection, baking, annealing, monitoring, testing, etc.) may be performed before, between, after, and during the steps shown in FIG. **19**.

[0076] While FIG. **19** generally describes a process for fabricating a single filter device, multiple filter devices may be fabricated simultaneously on a common wafer (consisting of a piezoelectric plate bonded to a substrate). In this case, each step of the process **1900** may be performed concurrently on all of the filter devices on the wafer.

[0077] The flow chart of FIG. **19** captures three variations of the process **1900** for making an XBAR which differ in when and how cavities are formed in the device substrate. The cavities may be formed at steps **1910**A, **1910**B, or **1910**C. Only one of these steps is performed in each of the three variations of the process **1900**.

[0078] The piezoelectric plate may be, for example, lithium niobate or lithium tantalate, either of which may be Z-cut, rotated Z-cut, or rotated YX-cut. The piezoelectric plate may be some other material and/or some other cut. The device substrate may preferably be silicon. The device substrate may be some other material that allows formation of deep cavities by etching or other processing.

[0079] In one variation of the process **1900**, one or more cavities are formed in the device substrate at **1910**A, before the piezoelectric plate is bonded to the substrate at **1915**. A separate cavity may be formed for each resonator in a filter device. The one or more cavities may be formed using conventional photolithographic and etching techniques. Typically, the cavities formed at **1910**A will not penetrate through the device substrate.

[0080] At **1915**, the piezoelectric plate is bonded to the device substrate. The piezoelectric plate and the device substrate may be bonded by a wafer bonding process. Typically, the mating surfaces of the device substrate and the piezoelectric plate are highly polished. One or more layers of intermediate materials, such as an oxide or metal, may be formed or deposited on the mating surface of one or both of the piezoelectric plate and the device substrate. One or both mating surfaces may be activated using, for example, a plasma process. The mating surfaces may then be pressed together with considerable force to establish molecular bonds between the piezoelectric plate and the device substrate or intermediate material layers.

[0081] At **1920**, the sacrificial substrate may be removed. For example, the piezoelectric plate and the sacrificial substrate may be a wafer of piezoelectric material that has been ion implanted to create defects in the crystal structure along a plane that defines a boundary between what will become the piezoelectric plate and the sacrificial substrate. At **1920**, the wafer may be split along the defect plane, for example by thermal shock, detaching the sacrificial substrate and leaving the piezoelectric plate bonded to the device substrate. The exposed surface of the piezoelectric plate may be polished or processed in some manner after the sacrificial substrate is detached.

[0082] Thin plates of single-crystal piezoelectric materials laminated to a non-piezoelectric substrate are commercially available. At the time of this application, both lithium niobate and lithium tantalate plates are available bonded to various substrates including silicon, quartz, and fused silica. Thin plates of other piezoelectric materials may be available now or in the future. The thickness of the piezoelectric plate may be between 300 nm and 1000 nm. When the substrate is silicon, a layer of SiO.sub.2 may be disposed between the piezoelectric plate and the substrate. When a commercially available piezoelectric plate/device substrate laminate is used, steps **1910**A, **1915**, and **1920** of the process **1900** are not performed.

[0083] A first conductor pattern, including IDTs and reflector elements of each XBAR, is formed at **1945** by depositing and patterning one or more conductor layers on the front side of the piezoelectric plate. The conductor layer may be, for example, aluminum, an aluminum alloy, copper, a copper alloy, or some other conductive metal. Optionally, one or more layers of other materials may be disposed below (i.e., between the conductor layer and the piezoelectric plate) and/or on top of the conductor layer. For example, a thin film of titanium, chrome, or other metal may be used to improve the adhesion between the conductor layer and the piezoelectric plate. A second conductor pattern of gold, aluminum, copper or other higher conductivity metal may be formed over portions of the first conductor pattern (for example the IDT bus bars and interconnections between the IDTs).

[0084] Each conductor pattern may be formed at **1945** by depositing the conductor layer and, optionally, one or more other metal layers in sequence over the surface of the piezoelectric plate. The excess metal may then be removed by etching through patterned photoresist. The conductor layer can be etched, for example, by plasma etching, reactive ion etching, wet chemical etching, or other etching techniques.

[0085] Alternatively, each conductor pattern may be formed at **1945** using a lift-off process. Photoresist may be deposited over the piezoelectric plate and patterned to define the conductor pattern. The conductor layer and, optionally, one or more other layers may be deposited in sequence over the surface of the piezoelectric plate. The photoresist may then be removed, which removes the excess material, leaving the conductor pattern.

[0086] Forming the first conductor pattern at **1945** includes controlling the sidewall angles of the conductors, or at least the IDT fingers. For example, a nominal sidewall angle may be within a range of 70° to 90°. A tolerance on the sidewall angle may be not less than or equal to ±2.5° from the nominal angle.

[0087] At **1950**, one or more frequency setting dielectric layer(s) may be formed by depositing one or more layers of dielectric material on the front side of the piezoelectric plate. For example, a dielectric layer may be formed over the shunt resonators to lower the frequencies of the shunt resonators relative to the frequencies of the series resonators. The one or more dielectric layers may be deposited using a conventional deposition technique such as physical vapor deposition, atomic layer deposition, chemical vapor deposition, or some other method. One or more lithography processes (using photomasks) may be used to limit the deposition of the dielectric layers to selected areas of the piezoelectric plate. For example, a mask may be used to limit a dielectric layer to cover only the shunt resonators.

[0088] At **1955**, a passivation/tuning dielectric layer is deposited over the piezoelectric plate and conductor patterns. The passivation/tuning dielectric layer may cover the entire surface of the filter except for pads for electrical connections to circuitry external to the filter. In some instantiations of the process **1900**, the passivation/tuning dielectric layer may be formed after the cavities in the device substrate are etched at either **1910**B or **1910**C.

[0089] In a second variation of the process **1900**, one or more cavities are formed in the back side of the device substrate at **1910**B. A separate cavity may be formed for each resonator in a filter device. The one or more cavities may be formed using an anisotropic or orientation-dependent dry or wet etch to open holes through the back side of the device substrate to the piezoelectric plate. In this case, the resulting resonator devices will have a cross-section as shown in FIG. **1**.

[0090] In a third variation of the process **1900**, one or more cavities in the form of recesses in the device substrate may be formed at **1910**C by etching the substrate using an etchant introduced through openings in the piezoelectric plate. A separate cavity may be formed for each resonator in a filter device. The one or more cavities formed at **1910**C will not penetrate through the device substrate.

[0091] Ideally, after the cavities are formed at **1910**B or **1910**C, most or all of the filter devices on a wafer will meet a set of performance requirements. However, normal process tolerances will result in variations in parameters such as the thicknesses of dielectric layer formed at **1950** and **1955**, variations in the thickness and line widths of conductors and IDT fingers formed at **1945**, and variations in the thickness of the piezoelectric plate. These variations contribute to deviations of the filter device performance from the set of performance requirements.

[0092] To improve the yield of filter devices meeting the performance requirements, frequency tuning may be performed by selectively adjusting the thickness of the passivation/tuning layer deposited over the resonators at **1955**. The frequency of a filter device pass-band can be lowered by adding material to the passivation/tuning layer, and the frequency of the filter device pass-band can be increased by removing material to the passivation/tuning layer. Typically, the process **1900** is biased to produce filter devices with pass-bands that are initially lower than a required frequency range but can be tuned to the desired frequency range by removing material from the surface of the passivation/tuning layer.

[0093] At **1960**, a probe card or other means may be used to make electrical connections with the filter to allow radio frequency (RF) tests and measurements of filter characteristics such as input-output transfer function. Typically, RF measurements are made on all, or a large portion, of the filter devices fabricated simultaneously on a common piezoelectric plate and substrate.

[0094] At **1965**, global frequency tuning may be performed by removing material from the surface of the passivation/tuning layer using a selective material removal tool such as, for example, a scanning ion mill as previously described. “Global” tuning is performed with a spatial resolution equal to or larger than an individual filter device. The objective of global tuning is to move the pass-band of each filter device towards a desired frequency range. The test results from **1960** may be processed to generate a global contour map indicating the amount of material to be removed as a function of two-dimensional position on the wafer. The material is then removed in accordance with the contour map using the selective material removal tool.

[0095] At **1970**, local frequency tuning may be performed in addition to, or instead of, the global frequency tuning performed at **1965**. “Local” frequency tuning is performed with a spatial resolution smaller than an individual filter device. The test results from **1960** may be processed to generate a map indicating the amount of material to be removed at each filter device. Local frequency tuning may require the use of a mask to restrict the size of the areas from which material is removed. For example, a first mask may be used to restrict tuning to only shunt resonators, and a second mask may be subsequently used to restrict tuning to only series resonators (or vice versa). This would allow independent tuning of the lower band edge (by tuning shunt resonators) and upper band edge (by tuning series resonators) of the filter devices.

[0096] After frequency tuning at **1965** and/or **1970**, the filter device is completed at **1975**. Actions that may occur at **1975** include forming bonding pads or solder bumps or other means for making connection between the device and external circuitry (if such pads were not formed at **1945**); excising individual filter devices from a wafer containing multiple filter devices; other packaging steps; and additional testing. After each filter device is completed, the process ends at **1995**.

[0097] In general, it is noted that throughout this description, the embodiments and examples shown should be considered as exemplars, rather than limitations on the apparatus and procedures disclosed or claimed. Although many of the examples presented herein involve specific combinations of method acts or system elements, it should be understood that those acts and those elements may be combined in other ways to accomplish the same objectives. With regard to flowcharts, additional and fewer steps may be taken, and the steps as shown may be combined or further refined to achieve the methods described herein. Acts, elements and features discussed only in connection with one embodiment are not intended to be excluded from a similar role in other embodiments.

[0098] As used herein, “plurality” means two or more. As used herein, a “set” of items may include one or more of such items. As used herein, whether in the written description or the claims, the terms “comprising”, “including”, “carrying”, “having”, “containing”, “involving”, and the like are to be understood to be open-ended, i.e., to mean including but not limited to. Only the transitional phrases “consisting of” and “consisting essentially of”, respectively, are closed or semi-closed transitional phrases with respect to claims. Use of ordinal terms such as “first”, “second”, “third”, etc., in the claims to modify a claim element does not by itself connote any priority, precedence, or order of one claim element over another or the temporal order in which acts of a method are performed, but are used merely as labels to distinguish one claim element having a certain name from another element having a same name (but for use of the ordinal term) to distinguish the claim elements. As used herein, “and/or” means that the listed items are alternatives, but the alternatives also include any combination of the listed items.

Claims

1. An acoustic resonator device comprising: a piezoelectric layer having a first surface and a second surface; and a first electrode and a second electrode on the first surface of the piezoelectric layer, wherein at least one of the first electrode and second electrode has a side that extends at an angle relative to the first surface of the piezoelectric layer, wherein the angle is greater than or equal to 70 degrees and less than 90 degrees, and wherein a thickness of the piezoelectric layer is less than a distance between a center of the first electrode and a center of the second electrode.

2. The acoustic resonator device of claim 1, wherein at least one of the first electrode and the second electrode has a trapezoidal cross-sectional shape, a substantially trapezoidal cross-sectional shape, or an irregular trapezoidal cross-sectional shape.

3. The acoustic resonator device of claim 2, wherein the substantially trapezoidal cross-sectional shape is substantially trapezoidal except for minor variations in structure due to manufacturing tolerances.

4. The acoustic resonator device of claim 1, wherein: the angle of the at least one of the first electrode and the second electrode is a first angle, and the side of the at least one of the first electrode and the second electrode is a first side, the acoustic resonator device further comprises a second side of the at least one the first electrode and second electrode; a second angle extends between the second side and the first surface of the piezoelectric layer, and at least one of the first electrode and the second electrode has an irregular trapezoidal cross-sectional shape that is defined by the first angle not being equal to the second angle.

5. The acoustic resonator device of claim 1, wherein the angle is between a line fit to the first surface of the piezoelectric layer and a line fit to the side of the at least one of the first electrode and second electrode.

6. The acoustic resonator device of claim 1, further comprising a substrate, wherein a portion of the piezoelectric layer is over a cavity between the substrate and the second surface of the piezoelectric layer.

7. The acoustic resonator device of claim 1, further comprising: a substrate; and an acoustic Bragg reflector between the second surface of the piezoelectric layer and the substrate.

8. The acoustic resonator device of claim 1, wherein the angle of the at least one of the first electrode and the second electrode is a first angle, and wherein at least one of the first electrode and second electrode comprises multiple layers of different materials.
9. The acoustic resonator device of claim 1, wherein: the angle of the at least one of the first electrode and the second electrode is a first angle, at least one of the first electrode and second electrode comprises multiple layers including an adhesion layer having a side at a second angle relative to the first surface of the piezoelectric layer, and the first angle is different than the second angle.
10. The acoustic resonator device of claim 1, wherein the thickness of the piezoelectric layer is an average thickness.
11. The acoustic resonator device of claim 1, wherein the thickness of the piezoelectric layer is measured between any point on the first surface and any point on the second surface in a direction substantially orthogonal to the either the first surface or the second surface.
12. The acoustic resonator device of claim 1, wherein the angle is defined as an internal angle between the side and the piezoelectric layer.
13. A bulk acoustic resonator device comprising: a piezoelectric layer having a surface; and an interdigital transducer (IDT) on the surface of the piezoelectric layer, the IDT comprising a plurality of interleaved fingers: wherein at least one of the plurality of interleaved fingers has a side surface at an angle that is greater than or equal to 70 degrees and less than 90 degrees relative to the surface of the piezoelectric layer, wherein a center-center distance between two adjacent interleaved fingers of the plurality of interleaved fingers is defined as a pitch, wherein a width of at least one of the plurality of interleaved fingers is defined as a mark of the at least one of the plurality of interleaved fingers, and wherein the pitch is between 2 to 20 times the mark.
14. The bulk acoustic resonator device of claim 13, wherein at least one of the plurality of interleaved fingers has a trapezoidal cross-sectional shape, a substantially trapezoidal cross-sectional shape, or an irregular trapezoidal cross-sectional shape.
15. The bulk acoustic resonator device of claim 14, wherein: the side surface is a first side surface and the angle is a first angle, the at least one of the plurality of interleaved fingers further comprises a second side surface, a second angle extends between the second side surface and the first surface of the piezoelectric layer, and the irregular trapezoidal cross-sectional shape is defined by the first angle not being equal to the second angle.
16. The bulk acoustic resonator device of claim 13, further comprising: a substrate; and either an acoustic Bragg reflector between the piezoelectric layer and the substrate, or a cavity between the piezoelectric layer and the substrate.
17. The bulk acoustic resonator device of claim 13, wherein the pitch is an average pitch of the plurality of interleaved fingers of the IDT.
18. The bulk acoustic resonator device of claim 13, wherein a thickness tp of the piezoelectric layer is measured in a substantially orthogonal direction to the surface of the piezoelectric layer, and wherein a ratio of tp to pitch is less than 0.5.
19. An acoustic filter, comprising: a plurality of bulk acoustic resonators, wherein at least one of the plurality of bulk acoustic resonators comprises: a piezoelectric layer having a surface; and an interdigital transducer (IDT) on the surface of the piezoelectric layer, the IDT comprising a plurality of interleaved fingers: wherein at least one of the plurality of interleaved fingers has a side surface at an angle that is greater than or equal to 70 degrees and less than 90 degrees relative to the surface of the piezoelectric layer, wherein a center-center distance between two adjacent interleaved fingers of the plurality of interleaved fingers is defined as a pitch, wherein a width of at least one of the plurality of interleaved fingers is defined as a mark of the at least one of the plurality of interleaved fingers, and wherein the pitch is between 2 to 20 times the mark.
20. The acoustic filter of claim 19, wherein: at least one of the plurality of interleaved fingers has a trapezoidal cross-sectional shape, a substantially trapezoidal cross-sectional shape, or an irregular

trapezoidal cross-sectional shape, wherein the substantially trapezoidal cross-sectional shape is substantially trapezoidal except for minor variations due to manufacturing tolerances, wherein for the irregular trapezoidal cross-sectional shape the side surface is a first side surface and the angle is a first angle, and. wherein the at least one of the plurality of interleaved fingers further comprises: a second side surface; and a second angle that extends between the second side surface and the first surface of the piezoelectric layer, and wherein the irregular trapezoidal cross-sectional shape is defined by the first angle not being equal to the second angle.