and V(T) is an excitation phase velocity. Further, an actual measurement may indicate TCF = (f(45°C) - f(25°C))/(20 x f(25°C)), where f(T) is a measured frequency, and a resonant frequency and/or anti-resonant frequency can be measured for a resonator whereas a center frequency can be measured for a filter. It is to be appreciated that, if a frequency is actually measured but does not linearly changed, then a maximum frequency variation within the measured temperature range can be divided by the measured temperature range to obtain a frequency variation per degree.

[0005] Thus, in order to obtain a required coupling factor and a better TCF, the present inventors and the like have developed a surface acoustic filter that is manufactured by firstly combining an LT/LN substrate having a negatives TCF with an SiO_2 thin film having a positive TCF to form a SiO_2 thin film/high-density electrode/LT or LN substrate structure and then removing protrusions on the SiO_2 thin film originated from the electrode to planarize the surface (for example, see Non-Patent Literature 1). This structure may result in a TCF of -10 ppm/°C, which is relatively better, and further a characteristic such as an impedance ratio and a Q that is the same as that of a single LT/LN substrate. The impedance ratio and the Q of this resonator may be around 60 dB and 800 respectively.

[0006] It is to be appreciated that a quartz substrate has a better thermal coefficient of frequency; however, its coupling factor, which indicates piezoelectric nature, can be smaller and would not satisfy the bandwidth requirement of the filter necessary to a smartphone or mobile phone. Further, according to a filter using a bulk wave of an AlN (aluminum nitride) film, the Q of the resonator can be 2000, which may be steeper in the filter characteristic as compared with a SAW filter, whereas the thermal coefficient of frequency can be -30 ppm/°C, which may not be so favorable.

Citation List

Non-Patent Literature

[0007] Non-Patent Literature 1: Michio Kadota, Takeshi Nakao, Kenji Nishiyama, Norio Taniguchi and Toshiyuki Fuyutsume, “Small Surface Acoustic Wave Duplexer Having Good Temperature Characteristics,” Institute of Electronics, Information and Communication Engineers (IEICE) TRANSACTIONS A, 2013, Vol.J96-A, No.6, pp.301-308

Summary ~~of Invention~~

~~Technical Problem~~

[0008] The acoustic wave filter as described in Non-Patent Literature 1 may result in a relatively better TCF; however, there have been problems that the amounts of the Q and impedance ratio of its resonator are similar to those of a

single LT or LN substrate and the steepness of the frequency characteristic has been far from being sufficient because the SiO_2 thin film is a columnar structure polycrystalline film.

[0009] The present ~~invention~~disclosure is made in view of such problems, and ~~has an object to~~ provides an acoustic wave device that has a better TCF and can improve the Q and impedance ratio of its resonator.

~~**Solution to Problem**~~

[0009a] In one aspect, the present disclosure refers to an acoustic wave device using a surface acoustic wave, comprising: a substrate containing 70 mass% or greater of silicon dioxide (SiO_2); a piezoelectric thin film formed of $LiTaO_3$ crystal or $LiNbO_3$ crystal, the piezoelectric thin film being disposed on the substrate; an interdigital transducer electrode disposed in contact with the piezoelectric thin film; and an insulating boundary film disposed between the substrate and the piezoelectric thin film, the boundary film having one or more layers, one layer closest to the piezoelectric thin film having a thickness indicated in Table 1 depending on a bulk shear wave phase velocity thereof.

Table 1

Sear wave phase velocity Vs (m/s)	Thickness T [wavelength]
1500 <= Vs1 <= 2200	0 < T <= 0.5
2200 < Vs2 <= 3400	0 < T <= 0.67
3400 < Vs3 <= 5900	0 < T <= 3
5900 < Vs4 <= 13000	0 < T <= 0.6

[0010] ~~To achieve the object as described above, a~~An acoustic wave device according to the present ~~invention~~disclosure may be an acoustic wave device using a surface acoustic wave, the acoustic wave device including a substrate containing 70 mass% or greater of silicon dioxide (SiO_2), a piezoelectric thin film formed of $LiTaO_3$ or $LiNbO_3$ crystal and disposed on the substrate, and an interdigital transducer electrode disposed in contact with the piezoelectric thin film, in which the piezoelectric thin film may include a piezoelectric thin plate.

[0011] In an acoustic wave device according to the present ~~invention~~disclosure, the substrate may preferably have a sheer wave phase velocity of a bulk wave ranging from 3,400 m/s to 4,800 m/s, which is close to the sheer wave velocity of LT or LN. Most of such substrates are isotropic and is not anisotropic in x-, y- and z-axes, whereas a quartz substrate that is a piezoelectric single crystal may be anisotropic and may have a different property. For this reason, when such a quartz substrate is used, it is preferable to configure the quartz substrate to have the phase velocity of the surface acoustic wave propagating along the

quartz substrate greater than the phase velocity of the surface acoustic wave propagating along the piezoelectric thin film. Further, the difference between the phase velocities may preferably be 300 m/s or greater, and more preferably be 600 m/s or greater. Further, in an acoustic wave device according to the present ~~invention~~disclosure, the surface acoustic wave may preferably be a leaky surface acoustic wave (LSAW). Still further, an SH (shear horizontal) component of the LSAW may preferably be 50% or greater, and more preferably be 65% or greater. Further, the surface acoustic wave may be an S wave having phase velocity of 4,500 m/s or greater. It is to be appreciated that whether the surface acoustic wave in use is a leaky surface acoustic wave or not can be theoretically determined by the Euler angles of the substrate.

[0012] A substrate containing 70 mass% or greater of silicon dioxide (SiO_2) may result in a positive TCF for a surface acoustic wave (SAW). Thus, in an acoustic wave device according to the present ~~invention~~disclosure, disposing a piezoelectric thin film formed of $LiTaO_3$ (LT) or $LiNbO_3$ (LN) crystal having a negative TCF on a substrate having a positive TCF may allow for a better TCF close to zero ppm/°C. Further, configuring the piezoelectric thin film formed of

LT or LN to have Euler angles to excite a leaky surface acoustic wave (LSAW) whereas configuring the substrate to have Euler angles for a phase velocity similar to or greater than the phase velocity enabled for the LSAW of LT or LN may allow an LSAW mode having no leaky component in the piezoelectric thin film to be used. Accordingly, an impedance ratio greater by 15 to 20 dB for example than the characteristic of an LT or LN single substrate can be obtained. Further, this impedance ratio may correspond to 6 times to 10 times in Q under the same bandwidths and thus may result in excellent steepness and insertion loss characteristics. Further, the coupling factor can be configured to be greater than that of the piezoelectric thin film itself, although the difference may be small.

[0013] The acoustic wave device according to the present ~~invention~~disclosure may include a grounded shunt electrode and/or an insulating bonding film between the substrate and the piezoelectric thin film. In this case, the device may have a structure such as: an interdigital transducer electrode/piezoelectric thin film/substrate structure; an interdigital transducer electrode/piezoelectric thin film/bonding film/substrate structure; an interdigital transducer electrode/piezoelectric thin film/shunt electrode/substrate structure; an interdigital transducer electrode/piezoelectric thin film/shunt electrode/bonding film/substrate structure; or an interdigital transducer electrode/piezoelectric thin film/bonding film/shunt electrode/substrate structure. In this case, the device may achieve a better TCF and a higher Q and impedance ratio without losing its superior characteristics, even if including a shunt electrode or a bonding film. Especially when having a shunt electrode, the coupling factor can be increased and the propagation loss of the leaky surface acoustic wave can be reduced. It is to be appreciated that the bonding film may preferably have no sound absorption and be formed of a hard material. For example, the bonding film may be formed from an Si film or SiO_2 film.

[0014] In the acoustic wave device according to the present ~~invention~~disclosure, the interdigital transducer electrode may be configured to have at least a lower portion embedded into the piezoelectric thin film and/or may be configured to have at least an upper portion protruding from the piezoelectric thin film. In this case, the device may have superior characteristics and achieve a higher impedance ratio even in any structure. Especially in a structure in which the entire portion or the lower portion of the interdigital transducer electrode is embedded in the piezoelectric thin film, the phase velocity may become faster and thus advantageous for higher frequencies. It is to be appreciated that, in this case, there may be an electrical shunt between the piezoelectric thin film and the substrate.

[0015] In an acoustic wave device according to the present ~~invention~~disclosure, the substrate may preferably contain 80 mass% or greater of silicon dioxide (SiO_2), and more preferably of 99 mass% or greater and less than 100 mass%. The substrate may more preferably be a fused quartz containing 100 mass% of SiO_2 and far more preferably be formed of quartz substrate that is a piezoelectric single crystal. Further, the substrate may allow the propagating surface acoustic wave to have a phase velocity ranging from 3,400 m/s to 4,800 m/s. Further, the substrate may be formed of an isotropic substrate other than a quartz substrate, and the piezoelectric thin film may have a thickness of 0.001 mm or greater and less than 0.01 mm. Further, the substrate may be formed of a quartz substrate and allow the propagating surface acoustic wave to have a phase velocity of 4,500 m/s or greater, 4,800 m/s or greater, or 5,000 m/s or greater. Any one of these configurations may provide excellent characteristics and result in a better TCF, a higher Q, and an impedance ratio. It is to be appreciated that, since a quartz substrate have a positive TCF greater than that of an isotropic substrate, any thickness can be accepted in the piezoelectric thin film.

[0016] There is no dependence on a propagation direction of an acoustic wave in an isotropic substrate except for a quartz substrate, whereas, in a substrate using quartz that is anisotropic, the characteristics of the quartz substrate may vary depending on the orientation angle or propagation direction (Euler angles) and therefore it is important to choose appropriate Euler angles. Firstly, for an acoustic wave according to the present ~~invention~~disclosure, it may be desirable to choose Euler angles such that the power flow angle (PFA) can be zero. This is because, if the Euler angles are greatly shifted from zero, an acoustic wave may propagate in a direction oblique with respect to an interdigital transducer electrode. Example Euler angles that allow the PFA to indicate approximately zero may include (0°±5°, 0°-180°, 40°±12°), (10°±5°, 0°-180°, 42°±8°), (20°±5°, 0°-180°, 50°±8°), (0°±5°, 0°-180°, 0°±5°), (10°±5°, 0°-180°, 0°±5°), (20°±5°, 0°-180°, 0°±5°), (0°±5°, 0°-180°, 90°±5°), (10°±5°, 0°-180°, 90°±5°), (20°±5°, 0°-180°, 90°±5°), and orientation angles equivalent thereto.

[0017] Further, in an acoustic wave device according to the present ~~invention~~disclosure, the substrate may have Euler angles such as (0°±5°, 0°-125°, 0°±5°), (0°±5°, 0°-36°, 90°±5°), (0°±5°, 172°-180°, 90°±5°), (0°±5°, 120°-140°, 30°-49°), (0°±5°, 25°-105°, 0°±5°), (0°±5°, 0°-45°, 15°-35°), (0°±5°, 10°-20°, 60°-70°), (0°±5°, 90°-180°, 30°-45°), (0°±5°, 0°±5°, 85°-95°), (90°±5°, 90°±5°, 25°-31°), and (0°±5°, 90°±5°, -3° to 3°). Still further, the substrate may have Euler angles such as (20°±5°, 120°±10°, 115°±10°), (0°±5°, 90°±5°, 0°±10°), (0°±5°, 90°±5°, 75°±10°), (0°±5°, 0°±5°, 0°±10°), and (0°±5°, 0°±5°, 60°±10°). These cases may provide a better TCF.

[0018] Further, the following phase velocities, Euler angles, and film thicknesses may be preferable to obtain characteristics of higher Qs and impedance ratios. In an acoustic wave device according to the present ~~invention~~disclosure, the substrate may have the acoustic wave propagating at a phase velocity of 4,500 m/s or greater and may have Euler angles of (0°±5°, 70°-165°, 0°±5°) or (0°±5°, 95°-155°, 90°±5°). Preferably, the substrate may have the acoustic wave propagating in a phase velocity of 4,800 m/s or greater and may have Euler angles of (0°±5°, 90°-150°, 0°±5°) or (0°±5°, 103°-140°, 90°±5°), and further may have the acoustic wave propagating in a phase velocity of 5,000 m/s or greater and may have Euler angles of (0°±5°, 100°-140°, 0°±5°) or (0°±5°, 110°-135°, 90°±5°).

[0019] Further, in an acoustic wave device according to the present ~~invention~~disclosure, the substrate may have Euler angles of (0°±5°, 0°-132°, 0°±5°), (0°±5°, 0°-18°, 0°±5°), (0°±5°, 42°-65°, 0°±5°) or (0°±5°, 126°-180°, 0°±5°), which may provide a positive TCF for a Rayleigh wave or LSAW, and the piezoelectric thin film may be formed of $LiTaO_2$ crystal and have Euler angles of (0°±5°, 82°-148°, 0°±5°). In this case, the substrate may preferably have Euler angles of (0°±5°, 0°-12°, 0°±5°), (0°±5°, 44°-63°, 0°±5°), or (0°±5°, 135°-180°, 0°±5°). Further, the piezoelectric thin film may preferably have Euler angles of (0°±5°, 90°-140°, 0±5°). This combination may result in a particularly good TCF.

[0020] Further, in an acoustic wave device according to the present ~~invention~~disclosure, the substrate may have Euler angles of (0°±5°, 0°-42°, 90°±5°), (0°±5°, 170°-190°, 90°±5°), (0°±5°, 0°-45°, 90°±5°), or (0°±5°, 123°-180°, 90°±5°), which may provide a positive TCF for a Rayleigh or an LSAW, and the piezoelectric thin film may be formed of $LiTaO_3$ crystal and may have Euler angles of (0°±5°, 80°-148°, 0°±5°). In this case, the substrate may preferably have Euler angles of (0°±5°, 0°-34°, 90°±5°) or (0°±5°, 126°-180°, 90°±5°). Further, the piezoelectric thin film may preferably have Euler angles of (0°±5°, 90°-140°, 0°±5°), more preferably of (0°±5°, 95°-143°, 0°±5°), and further more preferably of (0°±5°, 103°-125°, 0°±5°).

[0021] Further, in an acoustic wave device according to the present ~~invention~~disclosure, the substrate may have Euler angles with a high phase velocity LSAW of (1°-39°, 100°-150°, 0°-20° or 70°-120° or 160°-180°), and the piezoelectric thin film may be formed of $LiTaO_3$ crystal and have Euler angles of (0°±5°, 80°-148°, 0°±5°). Still further, the substrate may have Euler angles with a high phase velocity fast shear of around 5,000 m/s of (20°±5°, 120°±10°, 115°±10°), (0°±5°, 90°±5°, 0°±10°), (0°±5°, 90°, 75°±10°), (0°±5°, 0°, 0°±10°), or (0°±5°, 0°, 60°±10°).

[0022] Further, in an acoustic wave device according to the present ~~invention~~disclosure,

the substrate may have Euler angles of (0°±5°, 0°-23°, 0°±5°), (0°±5°, 32°-69°, 0°±5°), (0°±5°, 118°-180°, 0°±5°), (0°±5°, 0°-62°, 90°±5°), (0°±5°, 118°-180°, 90°±5°), (0°±5°, 0°-72°, 30°-60°), or (0°±5°, 117°-180°, 30°-60°), and the piezoelectric thin film may be formed of $LiTaO_3$ crystal and have Euler angles of (0°±5°, 80°-148°, 0°±5°). In this case, the Euler angles of the substrate may preferably be (0°±5°, 0°-12°, 0°±5°), (0°±5°, 37°-66°, 0°±5°), (0°±5°, 132°-180°, 0°±5°), (0°±5°, 0°-50°, 90°±5°), (0°±5°, 126°-180°, 90°±5°), (0°±5°, 0°-17°, 30°-60°), (0°±5°, 35°-67°, 30°-60°), or (0°±5°, 123°-180°, 30°-60°).

[0023] Further, in an acoustic wave device according to the present ~~invention~~disclosure, the piezoelectric thin film may be formed of $LiTaO_3$ crystal and have Euler angles of (90°±5°, 90°±5°, 33°-55°) or (90°±5°, 90°±5°, 125°-155°). Further, the piezoelectric thin film may be formed of $LiNbO_3$ crystal and have Euler angles of (90°±5°, 90°±5°, 38°-65°) or (90°±5°, 90°±5°, 118°-140°).

[0024] Further, in an acoustic wave device according to the present ~~invention~~disclosure, the piezoelectric thin film may be formed of a $LiTaO_3$ crystal and have a thickness between 0.001 times and 2 times the wave length of the acoustic wave. In this case, the thickness of the piezoelectric thin film may preferably be between 0.01 times and 0.6 times the wave length of the acoustic wave, more preferably be between 0.02 times and 0.6 times thereof, far more preferably be between 0.03 times and 0.4 times thereof, or still far more preferably be between 0.03 times to 0.3 times thereof.

[0025] Further, in an acoustic wave device according to the present ~~invention~~disclosure, the substrate may have Euler angles of (0°±5°, 0°-132°, 0°±5°), (0°±5°, 0°-18°, 0°±5°), (0°±5°, 42°-65°, 0°±5°), or (0°±5°, 126°-180°, 0°±5°), which may provide a positive TCF for a Rayleigh wave or LSAW, and the piezoelectric thin film may be formed of $LiNbO_3$ crystal and have Euler angles of (0°±5°, 75°-165°, 0°±5°), and preferably have Euler angles of (0°±5°, 100°-160°, 0°±5°). In this case, the substrate may preferably have Euler angles of (0°±5°, 0°-12°, 0°±5°), (0°±5°, 44°-63°, 0°±5°), or (0°±5°, 135°-180°, 0°±5°). Further, in this case, the piezoelectric thin film may preferably have a thickness between 0.001 times and 2 times the wavelength of the surface acoustic wave, more preferably between 0.01 times and 0.6 times, far more preferably between 0.012 times and 0.6 times, still far more preferably between 0.02 times and 0.5 times, or yet still far more preferably between 0.03 times and 0.33 times.

[0026] Further, in an acoustic wave device according to the present ~~invention~~disclosure, the substrate may have Euler angles of (0°±5°, 0°-42°, 90°±5°), (0°±5°, 90°-155°, 90°±5°), (0°±5°, 0°-45°, 90°±5°), or (0°±5°, 123°-

180°, 90°±5°), which may provide a positive TCF for a Rayleigh wave or an LSAW, and the piezoelectric thin film may be formed of $LiNbO_3$ crystal and may have Euler

angles of (0°±5°, 70°-170°, 0°±5°). In this case, the substrate may preferably have Euler angles of (0°±5°, 0°-34°, 90°±5°) or (0°±°, 126°-180°, 90°±5°). Further, in this case, the piezoelectric thin film may preferably have a thickness between 0.001 times and 2 times the wavelength of the surface acoustic wave, more preferably between 0.01 and 0.5 times, far more preferably between 0.02 and 0.33 times, still far more preferably between 0.06 times and 0.3 times.

[0027] Further, in an acoustic wave device according to the present ~~invention~~disclosure, the substrate may have Euler angles of (1°-39°, 100°-150°, 0°-20° or 70°-120° or 160°-180°), and the piezoelectric thin film may be formed of $LiNbO_3$ crystal and have Euler angles of (0°±5°, 95°-160°, 0°±5°). Further, in an acoustic wave device according to the present ~~invention~~disclosure, the substrate may have Euler angles of (1°-39°, 70°-150°, 0°-20° or 70°-120° or 160°-180°), and the piezoelectric thin film may be formed of $LiNbO_3$ crystal and have Euler angles of (0°±5°, 25°-51°, 0°±5°).

[0028] Further, in an acoustic wave device according to the present ~~invention~~disclosure, the substrate may have Euler angles of (0°±5°, 90°-178°, 0°±5°) or (0°±5°, 80°-160°, 90°±5°), and the piezoelectric thin film may be formed of $LiNbO_3$ crystal and have Euler angles for exciting a Rayleigh wave of (0°±5°, 35°-70°, 0°±5°), preferably (0°±5°, 45°-63°, 0°±5°), or more preferably (0°±5°, 48°-60°, 0°±5°). Further, in this case, the substrate providing a positive TCF for an LSAW and a Rayleigh wave may preferably have Euler angles of (0°±5°, 90°-178°, 0°±5°) or (0°±5°, 125°-160°, 90°±5°).

[0029] Further, in an acoustic wave device according to the present ~~invention~~disclosure, the substrate may have Euler angles of (0°±5°, 0°-16°, 0°±5°), (0°±5°, 42°-64°, 0°±5°), (0°±5°, 138°-180°, 0°±5°), (0°±5°, 0°-30°, 90°±5°), (0°±5°, 130°-180°, 90°±5°), (0°±5°, 0°-28°, 30°-60°), (0°±5°, 42°-70°, 30°-60°), or (0°±5°, 132°-180°, 30°-60°), and the piezoelectric thin film may be formed of $LiNbO_3$ crystal and have Euler angles of (0°±5°, 75°-165°, 0°±5°), or more preferably (0°±5°, 90°-160°, 0°±5°). In this case, the Euler angles of the substrate may more preferably be (0°±5°, 43°-61°, 0°±5°), (0°±5°, 147°-180°, 0°±5°), (0°±5°, 0°-15°, 90°±5°), (0°±5°, 134°-180°, 90°±5°), (0°±5°, 0°-23°, 30°-60°), (0°±5°, 43°-67°, 30°-60°), or (0°±5°, 137°-180°, 30°-60°).

[0030] Further, in an acoustic wave device according to the present ~~invention~~disclosure, the substrate may have Euler angles of (0°±5°, 32°-118°, 0°±5°), (0°±5°, 0°-30°, 90°±5°), (0°±5°, 173°-180°, 90°±5°), or (0°±5°, 0°-142°, 30°-60°), and the piezoelectric thin film may be formed of $LiNbO_3$ crystal and have Euler angles of (0°±5°, 35°-70°, 0°±5°), or preferably (0°±5°, 45°-63°, 0°±5°). In this case, the Euler angles of the substrate may preferably be (0°±5°, 40°-102°, 0°±5°), (0°±5°, 0°-17°, 90°±5°), (0°±5°, 175°-180°, 90°±5°), or

(0°±5°, 13°-130°, 30°-

60°).

[0031] Further, in an acoustic wave device according to the present ~~invention~~disclosure, a surface acoustic wave to be used may be either in a basic or 0-th mode or a higher order mode. In a case where a higher order mode is used, a piezoelectric thin film may preferably have a thickness between 0.35 times and 9.3 times the wavelength of a surface acoustic wave. Further, in a case where a shunt electrode is provided between a substrate and a piezoelectric thin film, the piezoelectric thin film may have a thickness between 0.5 times and 9 times the wavelength of a surface acoustic wave. In these cases, a higher impedance ratio can be obtained.

[0032] Here, Euler angles (φ, θ, ψ) are in right-handed system, and represent a cut surface of the substrate or the piezoelectric thin film and a propagation direction of the surface acoustic wave. In other words, for crystal axes X, Y and Z of crystal or LT or LN forming the substrate, an X'-axis can be obtained by φ-rotating the X-axis in counterclockwise about the Z-axis as a rotation axis. Next, a Z'-axis can be obtained by θ-rotating the Z-axis in counterclockwise about the X'-axis as a rotation angle. Then, the Z'-axis is defined as a normal line and a plane including the X'-axis is defined as a cut surface of the substrate or the piezoelectric thin film. Further, a direction obtained by ψ-rotating the X'-axis in counterclockwise about the Z'-axis as a rotation axis is defined as a propagation direction of a surface acoustic wave. Further, these rotations result in the movement of the Y-axis and provide an axis defined as a Y'-axis perpendicular to the X'-axis and the Z'-axis.

[0033] According to these definitions of the Euler angles, a 40°-rotation-Y-plate-X-direction propagation can be expressed as Euler angles of (0°, 130°, 0°) and a 40°-rotation-Y-plate-90°-X-direction propagation can be expressed as Euler angles of (0°, 130°, 90°), for example.

[0034] It is to be appreciated that, in an acoustic wave device according to the present ~~invention~~disclosure, the substrate and the piezoelectric thin film may not only have the Euler angles described above but also have crystallographically equivalent Euler angles. Even in this case, a better TCF and a characteristic of higher Q and impedance ratio can be obtained. Further, when the substrate or the piezoelectric thin film is cut out at desired Euler angles, an error of approximately ±0.5° at a maximum may be included for each component of the Euler angles. The shape of an IDT may include an error of approximately ±3° for the propagation direction ψ. The characteristics of the acoustic wave include substantially no characteristic difference caused by approximately ±5° shift for φ and ψ components of Euler angles (φ, θ, ψ).

~~Advantageous Effects of Invention~~

[0035] According to the present ~~invention~~disclosure, it may be possible to provide an acoustic wave device that has a better TCF and enables a resonator to have a Q and impedance ratio.

Brief Description of Drawings

[0036] Unless otherwise stated, an Al-IDT may refer to an interdigital transducer electrode including an aluminum electrode having a thickness of 0.08 wavelength. In the figures:

FIGS. 1(a), 1(b) and 1(c) are perspective views illustrating a conventional acoustic wave device having Al-IDT/piezoelectric substrate, an acoustic wave device according to an embodiment of the present invention, and an alternative example having a bonding film of the acoustic wave device of the present invention, respectively;

FIGS. 2(a) and 2(b) are graphs illustrating frequency characteristics of impedance (Z) of Al-IDT/(0°, 110°, 0°) LT substrate of a conventional acoustic wave resonator, and Al-IDT/(0°, 132°, 0°) LT substrate of a conventional acoustic wave resonator, respectively. In the graphs, frequencies for minimum Z and maximum Z are referred to as a resonance frequency (fr) and an anti-resonance respectively (fa) respectively, and the corresponding Zs are referred to as Zr and Za respectively. The bandwidth is expressed as (fa - fa)/fr and the impedance ratio is expressed as 20 x Log (Za/Zr);

FIGS. 3(a) and 3(b) are graphs illustrating frequency characteristics of impedance (Z) of an acoustic wave resonator having a structure of Al-IDT/(0°, 110°, 0°) LT thin film (thickness of 0.15 wavelength)/(0°, 130°, 90°)quartz substrate, and an acoustic wave resonator having a structure of Al-IDT/(0°, 120°, 0°) LT thin film (thickness of 0.15 wavelength)/(0°, 130°, 0°) quartz substrate, respectively;

FIGS. 4(a) and 4(b) are graphs illustrating frequency characteristics of impedance (Z) of an acoustic wave resonator having a structure of Al-IDT/(0°, 110°, 0°) LT thin film (thickness of 0.15 wavelength)/(0°, 130°, 30°)quartz substrate, and an acoustic wave resonator having a structure of Al-IDT/(0°, 110°, 0°) LT thin film (thickness of 0.15 wavelength)/(0°, 130°, 60°) quartz substrate, respectively;

FIG. 5 is a graph illustrating that Rayleigh wave and LSAW phase velocities can depend on a propagation direction ψ at a (0°, 130°, ψ) quartz substrate;

FIGS. 6(a) and 6(b) are graphs illustrating frequency characteristics of impedance (Z) of an acoustic wave resonator having a structure of Al-IDT/(0°, 132°, 0°) LT thin film/(110)Si substrate, and an acoustic wave resonator having a structure of Al-IDT/(0°, 132°, 0°) LT thin film/c-sapphire substrate,

Claims

1. An acoustic wave device using a surface acoustic wave, comprising:

a substrate containing 70 mass% or greater of silicon dioxide (SiO_2);

a piezoelectric thin film formed of $LiTaO_3$ crystal or $LiNbO_3$ crystal, the piezoelectric thin film being disposed on the substrate;

an interdigital transducer electrode disposed in contact with the piezoelectric thin film; and

an insulating boundary film disposed between the substrate and the piezoelectric thin film, the boundary film having one or more layers, one layer closest to the piezoelectric thin film having a thickness indicated in Table 1 depending on a bulk shear wave phase velocity thereof.

Table 1

Sear wave phase velocity Vs (m/s)	Thickness T [wavelength]
1500 <= Vs1 <= 2200	0 < T <= 0.5
2200 < Vs2 <= 3400	0 < T <= 0.67
3400 < Vs3 <= 5900	0 < T <= 3
5900 < Vs4 <= 13000	0 < T <= 0.6

2. The acoustic wave device of claim 1 wherein the boundary film has two layers, one layer closer to the piezoelectric thin film having a thickness indicated in Table 3 depending on a bulk shear wave phase velocity of each layer, a total film thickness of respective layers having a thickness indicated in Table 2.

Table 2

Combination of first and second layers	Total film thickness T [wavelength]
Vs1 Vs2	0 < T <= 1.17
Vs1 Vs3	0 < T <= 3.5
Vs1 Vs4	0 < T <= 1.1
Vs2 Vs3	0 < T <= 3.67
Vs2 Vs4	0 < T <= 1.27
Vs3 Vs4	0 < T <= 3.6

3. The acoustic wave device of claim 1 wherein the boundary film has three layers, one layer closest to the piezoelectric thin film having a thickness indicated in Table 3 depending on a bulk shear wave phase velocity of each

layer, a total film thickness of respective layers having a thickness indicated in Table 3.

Table 3

Combination of first, second and third layers			Total film thickness T [wavelength]
Vs1	Vs2	Vs1	0 < T <= 1.67
Vs1	Vs2	Vs3	0 < T <= 4.17
Vs1	Vs2	Vs4	0 < T <= 1.77
Vs1	Vs3	Vs1	0 < T <= 4.00
Vs1	Vs3	Vs4	0 < T <= 4.17
Vs1	Vs4	Vs1	0 < T <= 1.6
Vs2	Vs1	Vs2	0 < T <= 1.84
Vs2	Vs3	Vs2	0 < T <= 4.34
Vs2	Vs3	Vs4	0 < T <= 4.27
Vs3	Vs1	Vs3	0 < T <= 6.5
Vs3	Vs2	Vs3	0 < T <= 6.67
Vs3	Vs4	Vs3	0 < T <= 6.6
Vs4	Vs1	Vs4	0 < T <= 1.70
Vs4	Vs2	Vs4	0 < T <= 1.87
Vs4	Vs3	Vs4	0 < T <= 4.20

4. The acoustic wave device of claim 3 wherein a layer of the boundary film closest or second closest to the piezoelectric thin film includes 30 % or greater of SiO_2 or SiO and has a thickness of 0.001 times to 1.2 times a wavelength of the surface acoustic wave.

5. The acoustic wave device of claim 3 wherein a layer of the boundary film closest or second closest to the piezoelectric thin film includes 30 % or greater of SiO_2 or SiO and has a thickness of 0.001 times to 0.3 times a wavelength of the surface acoustic wave.

6. The acoustic wave device of claim 1 wherein the boundary film includes four layers, one layer closest to the piezoelectric thin film having a thickness indicated in Table 1 depending on a bulk shear wave phase velocity thereof.

~~1. An acoustic wave device using a surface acoustic wave, comprising:~~

~~a substrate containing 70 mass% or greater of silicon dioxide (SiO_2);~~

~~a piezoelectric thin film formed of $LiTaO_3$ crystal or $LiNbO_3$ crystal, the piezoelectric thin film being disposed on the substrate; and~~

~~an interdigital transducer electrode disposed in contact with the piezoelectric thin film.~~

~~2. The acoustic wave device of claim 1 further comprising a shunt electrode and/or an insulating boundary film between the substrate and the piezoelectric thin film.~~

~~3. The acoustic wave device of claim 1 or 2 wherein a phase velocity of the surface acoustic wave propagating along the substrate is configured to be greater than a phase velocity of the surface acoustic wave propagating along the piezoelectric thin film.~~

~~4. The acoustic wave device of any one of claims 1 to 3 wherein the interdigital transducer electrode is disposed for at least lower portion to be embedded in the piezoelectric thin film and/or at least upper portion to be protruded from the piezoelectric thin film.~~

~~5. The acoustic wave device of any one of claims 1 to 4 wherein the substrate includes a quartz substrate.~~

~~6. The acoustic wave device of any one of claims 1 to 5 wherein the substrate has a shear wave phase velocity of a bulk wave of 3,400 to 4,800 m/s.~~

~~7. The acoustic wave device of any one of claims 1 to 4 and 6 wherein the substrate includes an isotropic substrate, the piezoelectric thin film having a thickness of 0.001 mm or greater and less than 0.01 mm.~~

~~8. The acoustic wave device of any one of claims 1 to 7 wherein the substrate includes a quartz substrate and a phase velocity of the surface acoustic wave to propagate is 4,500 m/s or greater.~~

~~9. The acoustic wave device of any one of claims 1 to 7 wherein the substrate includes a quartz substrate and a phase velocity of the surface acoustic wave to propagate is 4,800 m/s or greater.~~

~~10. The acoustic wave device of any one of claims 1 to 7 wherein the substrate includes a quartz substrate and a phase velocity of the surface acoustic wave to propagate is 5,000 m/s or greater.~~

~~11. The acoustic wave device of any one of claims 1 to 10 wherein the substrate includes a quartz substrate, the surface acoustic wave to propagate being a leaky acoustic wave including primarily a SH component or an S wave having a phase velocity of 4,500 m/s or greater.~~

~~12. The acoustic wave device of any one of claims 1 to 11 wherein the substrate has the surface acoustic wave propagate in 4,500 m/s or greater and has Euler angles of (0°±5°, 70°-165°, 0°±5°), (0°±5°, 95°-155°, 90°±5°), or crystallographically equivalent Euler angles thereof.~~

~~13. The acoustic wave device of any one of claims 1 to 11 wherein the substrate has Euler angles of (0°±5°, 0°-125°, 0°±5°), (0°±5°, 0°-36°, 90°±5°), (0°±5°, 172°-180°, 90°±5°), (0°±5°, 120°-140°, 30°-49°), (0°±5°, 25°-105°, 0°±5°), (0°±5°, 0°-45°, 15°-35°), (0°±5°, 10°-20°, 60°-70°), (0°±5°, 90°-180°, 30°-45°), (0°±5°, 0°±5°, 85°-95°), (90°±5°, 90°±5°, 25°-31°), (0°±5°, 90°±5°, -3° to 3°), or crystallographically equivalent Euler angles thereof.~~

~~14. The acoustic wave device of any one of claims 1 to 11 wherein the substrate has Euler angles of (20°±5°, 120°±10°, 115°±10°), (0°±5°, 90°±5°, 0°±10°), (0°±5°, 90°±5°, 75°±10°), (0°±5°, 0°±5°, 0°±10°), (0°±5°, 0°±5°, 60°±10°), or crystallographically equivalent Euler angles thereof.~~

~~15. The acoustic wave device of any one of claims 1 to 14 wherein the piezoelectric thin film includes $LiTaO_3$ crystal and has Euler angles of (90°±5°, 90°±5°, 33°-55°), (90°±5°, 90°±5°, 125°-155°), or crystallographically equivalent Euler angles thereof.~~

~~16. The acoustic wave device of any one of claims 1 to 14 wherein the piezoelectric thin film includes $LiNbO_3$ crystal and has Euler angles of (90°±5°, 90°±5°, 38°-65°), (90°±5°, 90°±5°, 118°-140°), or crystallographically equivalent Euler angles thereof.~~

~~17. The acoustic wave device of any one of claims 1 to 11 wherein the substrate has Euler angles of (0°±5°, 0°-132°, 0°±5°), (0°±5°, 0°-18°, 0°±5°), (0°±5°, 42°-65°, 0°±5°), (0°±5°, 126°-180°, 0°±5°), or crystallographically equivalent Euler angles thereof, the piezoelectric thin film including $LiTaO_3$ crystal and having Euler angles of (0°±5°, 82°-148°, 0°±5°) or crystallographically equivalent Euler angles thereof.~~

18. The acoustic wave device of any one of claims 1 to 11 wherein the substrate has Euler angles of (0°±5°, 0°-42°, 90°±5°), (0°±5°, 170°-190°, 90°±5°), (0°±5°, 0°-45°, 90°±5°), (0°±5°, 123°-180°, 90°±5°), or crystallographically equivalent Euler angles thereof, the piezoelectric thin film including $LiTaO_3$ crystal and having Euler angles of (0°±5°, 80°-148°, 0°±5°) or crystallographically equivalent Euler angles thereof.

19. The acoustic wave device of claim 18 wherein the substrate has Euler angles of (0°±5°, 126°-180°, 90°±5°) or crystallographically equivalent Euler angles thereof.

20. The acoustic wave device of claim 18 or 19 wherein the piezoelectric thin film has Euler angles of (0°±5°, 103°-125°, 0°±5°) or crystallographically equivalent Euler angles thereof.

21. The acoustic wave device of any one of claims 1 to 11 wherein the substrate has Euler angles of (1°-39°, 100°-150°, 0°-20° or 70°-120° or 160°-180°) or crystallographically equivalent Euler angles thereof, the piezoelectric thin film including $LiTaO_3$ crystal and having Euler angles of (0°±5°, 80°-148°, 0°±5°) or crystallographically equivalent Euler angles thereof.

22. The acoustic wave device of any one of claims 1 to 11 wherein the substrate has Euler angles of (0°±5°, 0°-23°, 0°±5°), (0°±5°, 32°-69°, 0°±5°), (0°±5°, 118°-180°, 0°±5°), (0°±5°, 0°-62°, 90°±5°), (0°±5°, 118°-180°, 90°±5°), (0°±5°, 0°-72°, 30°-60°), (0°±5°, 117°-180°, 30°-60°), or crystallographically equivalent Euler angles thereof, the piezoelectric thin film including $LiTaO_3$ crystal and having Euler angles of (0°±5°, 80°-148°, 0°±5°) or crystallographically equivalent Euler angles thereof.

23. The acoustic wave device of any one of claims 17 to 22 wherein the piezoelectric thin film has a thickness of 0.001 times to 2 times a wavelength of the surface acoustic wave.

24. The acoustic wave device of any one of claims 17 to 22 wherein the piezoelectric thin film has a thickness of 0.01 times to 0.6 times a wavelength of the surface acoustic wave.

25. The acoustic wave device of any one of claims 1 to 11 wherein the

substrate has Euler angles of (0°±5°, 0°-132°, 0°±5°), (0°±5°, 0°-18°, 0°±5°), (0°±5°, 42°-65°, 0°±5°), (0°±5°, 126°-180°, 0°±5°), or crystallographically equivalent Euler angles thereof, the piezoelectric thin film including $LiNbO_3$ crystal and having Euler angles of (0°±5°, 75°-165°, 0°±5°) or crystallographically equivalent Euler angles thereof.

26. The acoustic wave device of any one of claims 1 to 11 wherein the substrate has Euler angles of (0°±5°, 0°-42°, 90°±5°), (0°±5°, 90°-155°, 90°±5°), (0°±5°, 0°-45°, 90°±5°), (0°±5°, 123°-180°, 90°±5°), or crystallographically equivalent Euler angles thereof, the piezoelectric thin film including $LiNbO_3$ crystal and having Euler angles of (0°±5°, 70°-170°, 0°±5°) or crystallographically equivalent Euler angles thereof.

27. The acoustic wave device of any one of claims 1 to 11 wherein the substrate has Euler angles of (1°-39°, 100°-150°, 0°-20° or 70°-120° or 160°-180°) or crystallographically equivalent Euler angles thereof, the piezoelectric thin film including $LiNbO_3$ crystal and having Euler angles of (0°±5°, 95°-160°, 0°±5°) or crystallographically equivalent Euler angles thereof.

28. The acoustic wave device of any one of claims 1 to 11 wherein the substrate has Euler angles of (0°±5°, 90°-178°, 0°±5°), (0°±5°, 80°-160°, 90°±5°), or crystallographically equivalent Euler angles thereof, the piezoelectric thin film including $LiNbO_3$ crystal and having Euler angles of (0°±5°, 35°-70°, 0°±5°) or crystallographically equivalent Euler angles thereof.

29. The acoustic wave device of any one of claims 1 to 11 wherein the substrate has Euler angles of (0°±5°, 0°-16°, 0°±5°), (0°±5°, 42°-64°, 0°±5°), (0°±5°, 138°-180°, 0°±5°), (0°±5°, 0°-30°, 90°±5°), (0°±5°, 130°-180°, 90°±5°), (0°±5°, 0°-28°, 30°-60°), (0°±5°, 42°-70°, 30°-60°), (0°±5°, 132°-180°, 30°-60°), or crystallographically equivalent Euler angles thereof, the piezoelectric thin film including $LiNbO_3$ crystal and having Euler angles of (0°±5°, 75°-165°, 0°±5°) or crystallographically equivalent Euler angles thereof.

30. The acoustic wave device of any one of claims 1 to 11 wherein the substrate has Euler angles of (0°±5°, 32°-118°, 0°±5°), (0°±5°, 0°-30°, 90°±5°), (0°±5°, 173°-180°, 90°±5°), (0°±5°, 0°-142°, 30°-60°), or crystallographically equivalent Euler angles thereof, the piezoelectric thin film including $LiNbO_3$ crystal and having Euler angles of (0°±5°, 35°-70°, 0°±5°) or crystallographically equivalent Euler angles thereof.

31. The acoustic wave device of any one of claims 25, 27, 28, 29 and 30 wherein the piezoelectric thin film has a thickness of 0.001 times to 2 times a wavelength of the surface acoustic wave.

32. The acoustic wave device of any one of claims 25, 27, 28, 29 and 30 wherein the piezoelectric thin film has a thickness of 0.012 times to 0.6 times a wavelength of the surface acoustic wave.

33. The acoustic wave device of any one of claims 26, 27, 28, 29 and 30 wherein the piezoelectric thin film has a thickness of 0.01 times to 0.5 times a wavelength of the surface acoustic wave.

34. The acoustic wave device of any one of claims 1 to 33 further comprising Si-containing film disposed between the substrate and the piezoelectric thin film, the Si-containing film containing 30% or greater of SiO_2 or SiO, the substrate having a shear wave phase velocity of a bulk wave of 5,900 m/s or greater, and the Si-containing film having a thickness of 0.15 times to 1 times a wavelength of the surface acoustic wave.

35. The acoustic wave device of any one of claims 1 to 33 further comprising Si-containing film disposed between the substrate and the piezoelectric thin film, the Si-containing film containing 30% or greater of SiO_2 or SiO, the substrate having a shear wave phase velocity of a bulk wave of 5,900 m/s or greater, and the Si-containing film having a thickness of 0.3 times to 0.5 times a wavelength of the surface acoustic wave.

36. The acoustic wave device of any one of claims 1 to 35 wherein the interdigital transducer electrode has a thickness indicated in Table 1 depending on a density thereof.

Table 1

Density range (kg/m^3)	Electrode thickness [wavelength (λ)]
2000-5000	0.005-0.32
5001-9500	0.005-0.20
9501-15000	0.005-0.28
15001-220000	0.005-0.20

37. The acoustic wave device of any one of claims 1 to 36 wherein the

interdigital transducer electrode has a metalization ratio indicated in Table 2 depending on a density thereof.

Table 2

Density range (kg/m^3)	Electrode metalization ratio
2000-5000	0.15-0.63
5001-9500	0.15-0.63
9501-15000	0.15-0.71
15001-220000	0.15-0.65

38. The acoustic wave device of any one of claims 1 to 37 further comprising an insulating boundary film disposed between the substrate and the piezoelectric thin film, the boundary film having a thickness of 0.34 wavelength or greater.

39. The acoustic wave device of any one of claims 1 to 37 further comprising an insulating boundary film disposed between the substrate and the piezoelectric thin film, the boundary film having one or more layers, one layer closest to the piezoelectric thin film having a thickness indicated in Table 3 depending on a bulk shear wave phase velocity thereof.

Table 3

Sear wave phase velocity Vs (m/s)	Thickness T [wavelength]
1500 <= Vs1 <= 2200	0 < T <= 0.5
2200 < Vs2 <= 3400	0 < T <= 0.67
3400 < Vs3 <= 5900	0 < T <= 3
5900 < Vs4 <= 13000	0 < T <= 0.6

40. The acoustic wave device of claim 39 wherein the boundary film has two layers, one layer closer to the piezoelectric thin film having a thickness indicated in Table 3 depending on a bulk shear wave phase velocity of each layer, a total film thickness of respective layers having a thickness indicated in Table 4.

Table 4

Combination of first and second layers	Total film thickness T [wavelength]
Vs1 Vs2	0 < T <= 1.17
Vs1 Vs3	0 < T <= 3.5
Vs1 Vs4	0 < T <= 1.1

Vs2 Vs3	0 < T <= 3.67
Vs2 Vs4	0 < T <= 1.27
Vs3 Vs4	0 < T <= 3.6

41. The acoustic wave device of claim 39 wherein the boundary film has three layers, one layer closest to the piezoelectric thin film having a thickness indicated in Table 3 depending on a bulk shear wave phase velocity of each layer, a total film thickness of respective layers having a thickness indicated in Table 5.

Table 5

Combination of first, second and third layers	Total film thickness T [wavelength]
Vs1 Vs2 Vs1	0 < T <= 1.67
Vs1 Vs2 Vs3	0 < T <= 4.17
Vs1 Vs2 Vs4	0 < T <= 1.77
Vs1 Vs3 Vs1	0 < T <= 4.00
Vs1 Vs3 Vs4	0 < T <= 4.17
Vs1 Vs4 Vs1	0 < T <= 1.6
Vs2 Vs1 Vs2	0 < T <= 1.84
Vs2 Vs3 Vs2	0 < T <= 4.34
Vs2 Vs3 Vs4	0 < T <= 4.27
Vs3 Vs1 Vs3	0 < T <= 6.5
Vs3 Vs2 Vs3	0 < T <= 6.67
Vs3 Vs4 Vs3	0 < T <= 6.6
Vs4 Vs1 Vs4	0 < T <= 1.70
Vs4 Vs2 Vs4	0 < T <= 1.87
Vs4 Vs3 Vs4	0 < T <= 4.20

42. The acoustic wave device of any one of claims 38 to 40 wherein a layer of the boundary film closest or second closest to the piezoelectric thin film includes 30 % or greater of SiO_2 or SiO and has a thickness of 0.001 times to 1.2 times a wavelength of the surface acoustic wave.

43. The acoustic wave device of any one of claims 38 to 40 wherein a layer of the boundary film closest or second closest to the piezoelectric thin film includes 30 % or greater of SiO_2 or SiO and has a thickness of 0.001 times to 0.3 times a wavelength of the surface acoustic wave.

~~44. The acoustic wave device of claim 39 wherein the boundary film includes four layers, one layer closest to the piezoelectric thin film having a thickness indicated in Table 3 depending on a bulk shear wave phase velocity thereof.~~

~~45. The acoustic wave device of any one of claims 1 to 44 wherein the surface acoustic wave has a higher order mode, the interdigital transducer electrode having a thickness indicated in Table 6 depending on a density thereof.~~

~~**Table 6**~~

~~Density range (kg/m^3)~~	~~Electrode thickness [wavelength]~~
~~2000-5000~~	~~0.17-0.8~~
~~5001-9500~~	~~0.08-0.44~~
~~9501-15000~~	~~0.08-0.43~~
~~15000-220000~~	~~0.06-0.4~~

~~46. The acoustic wave device of any one of claims 1 to 45 wherein the surface acoustic wave has a higher order mode, the piezoelectric thin film having a thickness of 0.35 times to 9.3 times a wavelength of the surface acoustic wave.~~

~~47. The acoustic wave device of any one of claims 1 to 46 wherein the surface acoustic wave is a leaky surface acoustic wave.~~

~~48. The acoustic wave device of any one of claims 1 to 16 wherein the surface acoustic wave is a longitudinal-wave-type leaky surface acoustic wave.~~

~~49. The acoustic wave device of any one of claims 1 to 15 and 25 to 46 wherein the piezoelectric thin film includes $LiNbO_3$ crystal, the surface acoustic wave being a Rayleigh wave.~~