

DESCRIPTION

SURFACE ACOUSTIC WAVE DEVICE, AND MOBILE COMMUNICATION
DEVICE AND SENSOR BOTH USING SAME

5 Technical Field

The present invention relates to surface acoustic wave devices having excellent pass-band characteristics particularly in a high-frequency band, and it also relates to mobile communication apparatuses and sensors both using the same devices.

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Background Art

A surface acoustic wave device (hereinafter referred to as a SAW device) is widely used as a filter or a resonator in radio apparatuses of mobile communication terminals because of its small size and lightweight. Since
15 the cellular phone system uses the higher frequencies, those filters used in the radio apparatuses of mobile communication terminals need to work in the high frequency range, among others, between 800 MHz and several GHz. Those filters are required to low loss in the pass-band, highly attenuate signals in the rejection band, and yet, to have steep filter characteristics.

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In general, application of a voltage to an inter-digital transducer (IDT), of which finger-electrodes formed on a piezoelectric-substrate mesh with each other, produces surface acoustic wave (SAW) propagating on the substrate. The SAW device excites and receives this SAW, thereby achieving the filter characteristics needed. The electrical characteristics of the SAW device is
25 determined based on mainly a shape and a structure of the IDT electrodes as well as the propagation characteristics of SAW propagating on the piezoelectric substrate. For instance, a SAW resonator, which is one of the

SAW devices, has the following relation:

$$v = 2 p f \text{ ----- equation (1)}$$

where p = pitch of the finger-electrodes of the IDT electrodes, v = phase velocity, namely, propagation speed of SAW, and f = resonance frequency.

5 Use of a SAW device at a high frequency band increases resonance frequency f , and if propagation speed v is constant, pitch p of IDT finger-electrodes must be reduced. It means that the pattern width of the IDT electrodes should be extremely narrowed, which results in lowering the manufacturing yield rate of the SAW devices. To avoid the lowering of the
10 yield rate, a piezoelectric substrate allowing SAW to propagate at a higher speed (v) is required. To obtain the characteristic of low loss, it is necessary to reduce propagation loss of SAW and resistance of the IDT electrode as much as possible.

 To obtain a SAW device such as a SAW filter and a SAW resonator of
15 low loss at a high frequency band, the foregoing points must be taken into account. The following two substrates have been thus widely used to obtain the SAW devices. A substrate made of single crystal LiTaO_3 (hereinafter referred to as LT single-crystal) is undergone 36° rotation and Y-cut. The SAW propagates in X direction of this resultant substrate, and this substrate
20 is called 36° Y-X LiTaO_3 substrate (hereinafter referred to as LT36 substrate.) A substrate made of single crystal LiNbO_3 (hereinafter referred to as LN single-crystal) is undergone 64° rotation and Y-cut. The SAW propagates in X direction of this resultant substrate, and this substrate is called 64° Y-X LiNbO_3 substrate (hereinafter referred to as LN64 substrate.) Use of those
25 LT36 substrate and LN64 substrate allows the SAW device to use leaky surface acoustic wave (LSAW) which propagates on the substrate while radiating bulk wave within the substrate.

The LSAW excited by those substrates has a feature of high phase velocity, i.e. propagation speed. Further, when the mass-load effect of the IDT electrode can be neglected, in other words, the film of the IDT electrode is thinner enough than the wavelength of LSAW to be propagated, the LSAW scarcely radiates the bulk wave. As a result, propagation loss due to the bulk wave can be substantially reduced. Thus LT36° substrate and LN64° substrate are fit to form SAW filters and SAW resonators of high-frequency and low loss. This is the reason why those two substrates have been widely used.

However, use of those substrate in SAW filters or SAW resonators at a frequency range between 800MHz – several GHz shortens the wavelength of SAW, so that the film thickness of the IDT electrode becomes as thick as several % – 10-odd % of the wavelength. Thus the mass-load effect of the IDT electrode cannot be neglected any longer. As a result, the propagation loss produced by propagating the LSAW cannot be neglected.

To overcome this problem, use of a substrate of which cut-angle is shifted to the larger angle is effective for substantial reduction of propagation loss. This idea is disclosed in Japanese Patent Application Non-Examined Publication No. H09-167936. According to this publication, the cut-angle of substrate, which minimizes the propagation loss of LSAW propagating on the LT single-crystal and LN single-crystal, varies in response to normalized film-thickness h/λ of IDT electrode, where h = film thickness of the electrode, λ = wavelength of SAW. In the case of LT single-crystal, when the film thickness of IDT electrode becomes 0.03 – 0.15 of the wavelength of LSAW (normalized film thickness h/λ is 3% – 15%), shift of the cut-angle from 36 to 39 – 46 can almost eliminate the propagation loss. In the same manner, in the case of LN single-crystal, when the film thickness of IDT

electrode becomes 0.03 – 0.15 of the wavelength of LSAW (normalized film thickness h/λ is 3% – 15%), shift of the cut-angle from 64° to the greater angle such as 66° – 74° can reduce the propagation loss to almost 0 (zero).

However, SAW filters and SAW resonators having different frequency characteristics have different pitches of IDT electrodes, in general. Thus if SAW filters or SAW resonators having different frequency characteristics with a flat film-thickness are manufactured, each one of the respective filters or resonators has its own optimum normalized film-thickness h/λ different from each other. As a result, a structure of two-filter in one-chip, where two SAW filters having different frequencies are formed on one chip, encounters the following problem: In general, the film thickness of IDT electrode is flat within one chip, thus it is difficult for those two SAW filters to reduce their propagation losses almost to 0 (zero) simultaneously. It is necessary to prepare an optimum film-thickness for each SAW filter within one chip to achieve this goal (propagation loss $\cong 0$). However, this goal makes the manufacturing steps complicate, and it is practically difficult to achieve this goal in the manufacturing floor.

Japanese Patent Application Non-Examined Publication No. H05-183380 discloses a method of attenuating signals outside the pass-band, and this method is expected to attenuate the signals to a greater degree than prior art. The method is to connect a reactance element to a ladder SAW filter, which is formed by coupling SAW resonators in a ladder shape, at an arm of the resonators coupled in parallel. The method actually can achieve substantial attenuation in a certain band-zone by widening the band to be attenuated; however, this method cannot improve substantially the steep needed for filter characteristics. Therefore, since the PCS, the standard of the cellular phone in the U.S., specifies its fractional cross-band {{{upper end

frequency of the cross-band) - (lower end frequency thereof)) / (center frequency thereof)} at 0.01, the pass-band is very close to the rejection band. In such a case, the foregoing method cannot practically attenuate signals in the rejection band close to the pass-band.

Disclosure of the Invention

The example embodiments aim to provide a SAW device having improved steep in characteristics, and reduced insertion loss, among others, of a SAW filter and a SAW resonator. The example embodiments also aim to provide a mobile communication apparatus and a sensor using the SAW device of the example embodiments. To be more specific, use a piezoelectric substrate cut out at a cut-angle which allows the substrate to excite LSAW, and reduce the phase velocity of SAW, which has been conventionally used as LSAW, to a speed slower than a speed of slow shear wave propagating on the substrate. Rayleigh surface acoustic wave (RSAW) theoretically free from propagation loss can be thus used, so that less insertion-loss than the SAW device using the conventional LSAW can be expected, and a steeper characteristics are also expected.

According to a first aspect of the present invention, there is provided a surface acoustic wave (SAW) device comprising:

a piezoelectric substrate that is cut out at a cut-angle allowing the substrate to excite a leaky surface acoustic wave (LSAW); and

an electrode pattern formed of an inter-digital transducer (IDT) electrode prepared on said substrate, the IDT electrode having at least a pair of finger-electrodes meshing with each other, wherein

a pitch p (m) of the finger-electrodes satisfies a relation of

$$2 X_p \leq v_b/f,$$

where v_b (m/s) is a phase velocity of slow shear wave propagating on said substrate, and f (Hz) is a resonance frequency of the SAW device.

This structure may allow the LSAW to suppress the radiation of bulk-wave, and propagates the LSAW as RSAW thereby reducing the propagation loss to almost 0 (zero). As a result, a SAW device having a lower insertion loss than the case where the conventional LSAW is used and being excellent in steep characteristics is obtainable.

In addition to the foregoing structure, the SAW device may further comprise a step formed on the surface of the piezoelectric substrate, and the step may have a similar pitch to the pitch "p" of the finger-electrodes which are formed on the top of this step. This structure may allow obtaining a SAW device having a lower insertion loss than the case where the conventional LSAW is used and being excellent in the steep characteristics. Use of LSAW as RSAW may incur reduction in reflection coefficient per electrode, however, this reduction may be also improved at the same time. As a result, ripples in transmission characteristics of the SAW device may be suppressed.

The SAW device may further comprise dielectric film formed on the electrode pattern such that it covers at least the electrode pattern. This structure may allow lowering the phase velocity due to the dielectric film formed, so that a SAW resonator having less insertion loss than the case where the conventional LSAW is used and being excellent in the steep characteristics is obtainable.

In accordance with a second aspect of the present invention, there is provided a surface acoustic wave (SAW) device comprising:

a piezoelectric substrate cut out at a cut-angle allowing

the substrate to excite a leaky surface acoustic wave (LSAW);

an electrode pattern formed of an inter-digital transducer (IDT) electrode prepared on said substrate, the IDT electrode having at least a pair of finger-electrodes meshing with each other; and

a dielectric film disposed over said electrode pattern for covering at least said electrode pattern, wherein

a pitch $p(m)$ of the finger-electrodes satisfies a relation of

$$2 \lambda_p \lambda_{f_{\text{before}}} \leq v_b \leq 2 \lambda_p \lambda_{f_{\text{after}}}$$

where f_{before} (Hz) is a resonance frequency of the SAW device before said dielectric film is formed, f_{after} (Hz) is that of after said dielectric film is formed and v_b (m/s) is a phase velocity of a slow shear wave propagating on said substrate.

The foregoing structure may allow a SAW resonator to reduce insertion loss from that uses conventional LSAW even if the phase velocity becomes higher due to the dielectric film formed thereon, and a SAW device excellent in the steep characteristics may be obtainable.

In the SAW device having the foregoing structure, the finger-electrodes may be made of aluminum or made from metal mainly comprising aluminum. In this construction, the following relation is satisfied: $hL \leq h_r$,

where hL = a film thickness of IDT electrode of LSAW-based device formed of this piezoelectric substrate using LSAW, and h_r = a film thickness of IDT electrode of the SAW device having the same resonance frequency as the foregoing LSAW-base device.

This structure may allow lowering the propagation speed of LSAW due to mass-load of the IDT electrode, and at the same time, allow suppressing an

increase of the resistance of the electrode film caused by the film thickness of the IDT electrode. As a result, a SAW device having low loss and excellent in the steep characteristics may be obtainable.

The SAW device in the foregoing structure may use metal, of which density is greater than aluminum, at least in the finger-electrodes. According to this structure, at least the finger-electrodes of IDT electrode may be made of the metal having a greater density than aluminum, so that lowering of the reflection coefficient per electrode may be restrained (= improved). As a result, the ripples occurring in the pass-band or on somewhat higher frequency side may be suppressed, and a SAW device excellent in the steep characteristics may be obtainable.

In the SAW device with the foregoing structure, at least the finger-electrodes may be formed of at least two layers, i.e., a first layer formed of metal of which density is greater than aluminum, and a second layer formed of aluminum or metal comprising mainly aluminum. This structure may allow improving the lowering of the reflection coefficient per electrode. As a result, the ripples occurring in the transmission characteristics may be suppressed, and at the same time, the increasing of resistance of the electrodes may be suppressed, so that a SAW device with low-loss and excellent in the steep characteristics may be obtainable.

The SAW device in the foregoing structure may have a piezoelectric substrate made of single-crystal of LiTaO_3 (LT single-crystal). This structure may allow forming a SAW device using the conventional LSAW together with the SAW device of the example embodiments on one chip.

The SAW device in the foregoing structure may include the piezoelectric substrate made of LT single-crystal, and this substrate may have a cut-face cut out along the following orientation: with respect

to X-axis of the LT single-crystal, the crystal is rotated along the direction from Y-axis to Z-axis by an angle ranging between not less than 26° and not more than 50° . The substrate may also have characteristics that may excite leaky surface acoustic wave (LSAW). When a SAW device using the conventional LSAW and the SAW device of the example embodiments are formed together on one chip, i.e. a SAW device of a two-device in one-chip is formed, the structure discussed above may allow both of the SAW devices to produce low losses and be excellent in the steep characteristics.

The SAW device of the example embodiments in the foregoing structure has a piezoelectric substrate made of single-crystal of LiNbO_3 (LN single-crystal). When a SAW device using the conventional LSAW and the SAW device of the example embodiments are formed together on one chip, i.e. a SAW device of a two-device in one-chip is formed, this structure may allow producing excellent characteristics.

The SAW device in the foregoing structure may include the piezoelectric substrate made of LN single-crystal. This substrate may have a cut-face cut out along the following orientation: with respect to X-axis of the LN single-crystal, the crystal is rotated along the direction from Y-axis to Z-axis by an angle ranging between not less than 50° and not more than 80° . The substrate may also have characteristics that may excite leaky surface acoustic wave (LSAW). When a SAW device using the conventional LSAW and the SAW device of the example embodiments are formed together on one chip, i.e. a SAW device of two-device in one-chip is formed, this structure may allow both of the SAW devices to produce small losses and be excellent in the steep characteristics.

The SAW device in the foregoing structure may include a plurality of the foregoing SAW devices formed on one chip. This

structure may allow the SAW device to produce low loss and have a steep selectivity of frequencies.

A mobile communication apparatus may employ the SAW devices discussed above, so that the SAW device of low-loss and steep characteristics works in the mobile communication apparatus. As a result, a compact, light-weighted and slim mobile communication apparatus such as cellular phone may be obtainable.

A sensor may employ the SAW device of low-loss and steep characteristics, which is developed by the method disclosed in the example embodiments, as a sensing section, so that a compact, light-weighted, and sensitive sensor is obtainable. This sensor may be suitable for sensing a temperature; however, it may be used for sensing smell or water content.

In accordance with a third aspect of the present invention, there is provided a method of designing a surface acoustic wave (SAW) device which comprises: a piezoelectric substrate cut out at a cut-angle allowing the substrate to excite a leaky surface acoustic wave (LSAW); and an electrode pattern formed of an inter-digital transducer (IDT) electrode prepared on said substrate, the IDT electrode having at least a pair of finer-electrodes meshing with each other, the method determining said electrode pattern and the cut-angle to satisfy a relation of $2Xp \leq vb/f$, where p (m) is a pitch of the finger-electrodes of said electrode pattern, vb (m/s) is a phase velocity of a slow shear wave propagating on said substrate, and f (Hz) is a resonance frequency of the SAW device.

In accordance with a fourth aspect of the present invention, there is provided a method of designing a surface acoustic wave (SAW) device which comprises: a piezoelectric substrate cut out at a cut-angle allowing the substrate to excite a leaky surface acoustic wave (LSAW); an electrode pattern formed of an inter-digital transducer (IDT) electrode prepared on said substrate, the IDT electrode having at least a pair of finger-electrodes meshing with each

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other; and a dielectric film disposed over said electrode pattern for covering at least said electrode pattern, the method determining said electrode pattern, the cut-angle and material of said dielectric film to satisfy a relation of $2 \times p \times f_{\text{before}} \leq v_b \leq 2 \times p \times f_{\text{after}}$, where f_{before} (Hz) is a resonance frequency of the SAW device before said dielectric film is formed, f_{after} (Hz) is that of after said dielectric film is formed, p (m) is a pitch of the finger electrodes of said electrode pattern, v_b (m/s) is an phase velocity of a slow shear wave propagating on said substrate.

Brief Description of the Drawings

Fig. 1A shows a perspective view of 1-port SAW resonator produced as an example of a SAW device in accordance with a first exemplary embodiment of the present invention.

Fig. 1B shows a sectional view taken along the line t-t of Fig. 1A.

Fig. 1C shows an enlarged sectional view of one cycle of IDT electrode used in the first embodiment.

Fig. 2 shows a relation between a propagation loss of LSAW on 39° Y-XLT substrate and a normalized film thickness of the IDT electrode.

Fig. 3A shows transmission characteristics of 1-port SAW resonator of sample 1 used in the first embodiment.

Fig. 3B shows transmission characteristics of a comparison sample 1 with sample 1 of 1-port SAW resonator used in the first embodiment.

Fig. 3C shows transmission characteristics of a comparison sample 2

with the 1-port SAW resonator in accordance with the first embodiment.

Fig. 4 is used for finding an index of sharpness in the first embodiment.

Fig. 5 is used for finding an index of insertion loss in the first embodiment.

5 Fig. 6 is used for finding an index of attenuation degree outside the pass-band.

Fig. 7A shows a perspective view illustrating a structure of a ladder SAW filter in accordance with a second exemplary embodiment of the present invention.

10 Fig. 7B shows a circuit diagram of the ladder SAW filter in accordance with the second embodiment.

Fig. 8 shows a relation between a propagation loss of LSAW on LT42° substrate and a normalized film thickness of the IDT electrode.

15 Fig. 9A shows transmission characteristics of sample 2 of ladder SAW filter in the second embodiment.

Fig. 9B shows transmission characteristics of comparison sample 3 with the ladder SAW filter in accordance with the second embodiment.

Fig. 10 illustrates a definition of shape factor in the second embodiment.

20 Fig. 11A shows transmission characteristics of sample 3 of 1-port SAW resonator used in the third embodiment.

Fig. 11B shows transmission characteristics of sample 4 of 1-port SAW resonator used in the third embodiment.

25 Fig. 11C shows transmission characteristics of sample 5 of 1-port SAW resonator used in the third embodiment.

Fig. 11D shows transmission characteristics of sample 6 of 1-port SAW resonator used in the third embodiment.

Fig. 11E shows transmission characteristics of comparison sample 4 with 1-port SAW resonator in accordance with the third embodiment.

Fig. 12A shows a sectional view illustrating parts of 1-port SAW resonator of sample 7 in accordance with the fourth exemplary embodiment of
5 the present invention.

Fig. 12B shows a sectional view illustrating parts of 1-port SAW resonator of sample 7 in accordance with the fourth embodiment.

Fig. 13A shows transmission characteristics before dielectric film is formed in 1-port SAW resonator of sample 7 in the fourth embodiment.

10 Fig. 13B shows transmission characteristics after the dielectric film is formed in 1-port SAW resonator of sample 7 in the fourth embodiment.

Fig. 14A shows transmission characteristics before dielectric film is formed in 1-port SAW resonator of sample 8 in the fourth embodiment.

15 Fig. 14B shows transmission characteristics after the dielectric film is formed in 1-port SAW resonator of sample 8 in the fourth embodiment.

Fig. 15 shows transmission characteristics of comparison sample 5 with 1-port SAW resonator in accordance with the fourth embodiment.

Fig. 16 shows transmission characteristics of comparison sample 6 with 1-port SAW resonator in accordance with the fourth embodiment.

20 Fig. 17A shows transmission characteristics of a ladder SAW filter for 800 MHz band out of two-filters in one-chip SAW filters of sample 9 in accordance with a fifth exemplary embodiment of the present invention.

Fig. 17B shows transmission characteristics of a ladder SAW filter for 1.9 GHz band out of a two-filter in one-chip SAW filter of sample 9 used in the
25 fifth embodiment.

Fig. 18A shows transmission characteristics of a ladder SAW filter for 800 MHz band out of a two-filter in one-chip SAW filter of sample 10 used in

the fifth embodiment.

Fig. 18B shows transmission characteristics of a ladder SAW filter for 1.9 GHz band out of a two-filter in one-chip SAW filter of sample 10 used in the fifth embodiment.

5 Fig. 19A shows transmission characteristics of a ladder SAW filter for 800 MHz band out of a two-filter in one-chip SAW filter of comparison sample 7 used in the fifth exemplary embodiment.

Fig. 19B shows transmission characteristics of a ladder SAW filter for 1.9 GHz band out of two-filter in one-chip SAW filter of comparison sample 7
10 used in the fifth embodiment.

Fig. 20A shows transmission characteristics of a ladder SAW filter for 800 MHz band out of two-filter in one-chip SAW filter of comparison sample 8 used in the fifth exemplary embodiment.

Fig. 20B shows transmission characteristics of a ladder SAW filter for
15 1.9 GHz band out of two-filter in one-chip SAW filter of comparison sample 8 used in the fifth embodiment.

Fig. 21 shows a schematic diagram illustrating a basic structure of a SAW device used as a temperature sensor in a sixth exemplary embodiment of the present invention.

20 Fig. 22 shows a relation between ambient temperatures and anti-resonance frequencies in the sixth embodiment.

Preferred Embodiments of the Invention

Exemplary embodiments of the SAW device disclosed in the present
25 invention are demonstrated hereinafter with reference to the accompanying drawings.

Exemplary Embodiment 1

Fig. 1A shows a perspective view of 1-port SAW resonator produced as an example of a SAW device in accordance with the first exemplary embodiment of the present invention. SAW resonator 2 is formed on piezoelectric substrate 1, and SAW resonator 2 is formed of IDT electrode 3 and reflector 4. Fig. 1B shows a sectional view taken along the line t-t of Fig. 1A. Fig. 1C shows an enlarged sectional view of one cycle of the IDT electrode, and the sectional view illustrates that finger-electrodes 301 are formed on substrate 1 at a given pitch "p".

10 In this embodiment, an LT substrate of 39° Y-cut and on which the SAW propagates along X-axis (hereinafter referred to as 39 Y-XLT substrate) is used as piezoelectric substrate 1. A phase velocity "vb" of the slow shear wave that propagates on substrate 1 is 3350.8 m/s. The electrodes of SAW resonator 2 formed on piezoelectric substrate 1 are made of Al-Cu alloy, namely, Cu is added to Al. The electrodes of the SAW resonator include at least an IDT electrode and an electrode of the resonator.

Sample 1 of the first embodiment is SAW resonator 2 of which finger-electrodes 301 have a pitch of 0.8 μm and a normalized film thickness h/λ of 19.4%. This SAW resonator 2 has a resonance frequency $f = 1891.4\text{ MHz}$, and the phase velocity thereof calculated using equation (1) is 3026.2 m/s. This speed is slower than the phase velocity vb of the slow shear wave on 39 Y-XLT substrate used in this embodiment. Based on the foregoing numerical values, the following equation is found: $2 \times p = 1.60 \times 10^{-6}$, $vb / f = 3350.8 / (1891.4 \times 10^6) = 1.772 \times 10^{-6}$. Thus the relation of $2 \times p \leq vb / f$ is satisfied.

25 A saw resonator as comparison sample 1 has the following specification: pitch "p" of finger-electrodes 301 is 1.06 μm , normalized film thickness h/λ is 6.0%. Another SAW resonator as comparison sample 2 has the following

specification: pitch "p" of finger-electrodes 301 is $1.0\mu\text{m}$, normalized film thickness h/λ is 11%. Those samples have resonance frequencies of 1886.0MHz (comparison sample 1) and 1884.9MHz (comparison sample 2). The acoustic velocities of those comparison samples can be found by equation (1) and their own resonance frequencies f, namely, comparison sample 1 has 3998.3 m/s, and comparison sample 2 has 3769.8 m/s. Those velocities are faster than the phase velocity of the slow shear wave propagating on 39° Y-XLT substrate used in this first embodiment. On top of that, both of those two comparison samples do not satisfy the relation of $2 \times p \leq v_b / f$.

Fig. 2 shows a relation between a propagation loss of LSAW on 39° Y-XLT substrate and a normalized film thickness h/λ of the IDT electrode. As Fig. 2 illustrates, a propagation loss of this LSAW propagating on piezoelectric substrate 1 takes a minimum value when the normalized film thickness h/λ becomes approx. 6%.

Fig. 3A shows transmission characteristics of SAW resonator 2 of sample 1 used in the first embodiment. Fig. 3B shows transmission characteristics of comparison sample 1, and Fig. 3C shows transmission characteristics of comparison sample 2.

In this embodiment, the SAW resonator is produced in the following way, and its characteristics are evaluated in the following manner: Electrode film is formed on piezoelectric substrate 1 by the magnetron-sputtering method, then a given electrode pattern of the SAW resonator is formed by the dry-etching method using the photo-lithography process and chlorine-based etching gas.

Electrical characteristics are measured using a RF (Radio Frequency) probe. The steep, one of the transmission characteristics, is compared by the method illustrated in Fig. 4. To be more specific, as shown in Fig. 4, point B2

of the transmission characteristics is specified as anti-resonance point, and point B1 is specified at lower side by 20MHz from anti-resonance frequency f_2 corresponding to anti-resonance point B2. A tilt of the linear line (the broken line in Fig. 4) connecting B1 to B2 is taken as an index representing the steep, characteristics where the index is normalized by a frequency at the middle point between B1 and B2, and $f_2 - f_1 = 20\text{MHz}$ is found. Thus the greater steep characteristics of the resonator, the less insertion loss, and the greater attenuation can be expected at the greater index of the steep characteristics. The index can be found by the following equation:

$$\text{Steep Index} = \{(ATT2 - ATT1) / 20\} / (f_1 + 10)$$

An index for comparing insertion loss is evaluated by the method shown in Fig. 5. To be more specific, as shown in Fig. 5, find frequency f_3 at point B3 where attenuation becomes 10dB on a lower frequency band side than anti-resonance frequency f_2 at anti-resonance point B2. Then find frequency f_4 at point B4 of which frequency is lower than f_3 by 20MHz, and the insertion loss at B4 is taken as an index of insertion loss. As a result, when a ladder filter is produced using the foregoing SAW resonators, the index of insertion loss is obtainable with a necessary attenuation maintained.

On the other hand, an index of attenuation outside the pass-band is evaluated by a method shown in Fig. 6, namely, find point B5 of which frequency f_5 is higher than f_2 by 30MHz, and an attenuation degree at f_5 is used for comparison.

The foregoing three indexes are used for comparing the characteristics of SAW resonators of sample 1, comparison sample 1, and comparison sample 2. Table 1 tells the result. As discussed above, piezoelectric substrate 1 uses 39 Y-XLT substrate, and the electrodes are made of Al-Cu alloy.

TABLE 1

	Pitch between finger electrodes p (μm)	Normalized film thickness H/λ (%)	Resonance frequency f (MHz)	SAW velocity (m/s)
Sample 1	0.8	19.4	1891.4	3026.2
Comparison sample 1	1.06	6.0	1886.0	3998.3
Comparison sample 2	1.0	11.0	1884.9	3769.8
	Insertion-loss index (dB)	Steep index	Attenuation index (dB)	
Sample 1	-0.7	2184.9	-4.6	
Comparison sample 1	-1.1	2062.5	-4.8	
Comparison sample 2	-1.9	1613.8	-5.5	

As table 1 tells, sample 1 has a higher steep-index than comparison sample 1 and comparison sample 2, and smaller insertion loss, so that sample 1 has better characteristics than the two comparison samples. If the SAW resonator of sample 1 uses LSAW as the conventional one does, normalized film thickness h/λ is 19.4%, so that the propagation loss is far greater than those of comparison samples 1 and 2 as shown in Fig. 2, and a greater loss is expected. However, the index of insertion loss of sample 1 actually shows a better result than comparison samples 1 and 2. This result tells that the phase velocity of SAW resonator of sample 1 decreases to lower than phase velocity v_b of the slow shear wave propagating on 39° Y – XLT substrate. As a result, the wave, which should have propagated in the LSAW mode, actually propagates in Rayleigh SAW (RSAW) mode. Thus propagation loss becomes almost 0 (zero), so that the characteristics of both loss and steep seem to improve. This is because electrode pitch “ p ” is set so that the relation of $2 \times p$

$\leq v_b / f$ can be satisfied using the foregoing piezoelectric substrate 1.

The steep characteristic is of course affected by the reduction of loss; but it can be also affected by a change of electromagnetic coupling coefficient. In particular, when the film thickness of the electrodes of the SAW resonator is increased, effective coupling coefficient "keff" increases in general, and as a result, the capacity ratio γ lowers, thereby lowering the sharpness. However, although sample 1 has a thicker film than the comparison samples 1 and 2, it shows the higher sharpness and better characteristics. Thus the wave which should have propagated in LSAW mode seems to actually propagate in RSAW mode, so that the coupling coefficient lowers simultaneously.

When comparison samples 1 and 2 are compared with each other, comparison sample 1 is more excellent in the insertion loss and the sharpness. This result tells that it seems that the SAWs of both comparison samples 1 and 2 propagate in conventional LSAW mode, and yet, as shown in Fig. 2, comparison sample 1 uses the normalized film thickness h/λ of approx. 6% at which the propagation loss of the LSAW becomes almost 0 (zero). This result agrees with the content disclosed Japanese Patent Application Non-Examined Publication No. H09-167936. Meanwhile, the acoustic velocities of comparison samples 1 and 2 are faster than that of the slow shear wave propagating on 39 Y - XLT substrate, thus the waves of those two comparison samples prove to propagate in the conventional LSAW mode.

The foregoing discussion proves the effective method for obtaining the SAW device with low-loss and steep is this: SAW device 2 is formed on piezoelectric substrate 1, which is cut out at the cut angle that allows substrate 1 to excite the LSAW, in such a manner that the relation of $2 \times p \leq v_b / f$ can be satisfied.

To be more specific, use the electrode made of aluminum or metal comprising mainly aluminum, and use piezoelectric substrate 1 comprising LT single-crystal having a cut-face cut out at a rotation angle between not less than 26° and not more than 50° from Y-axis to Z-axis with respect to X-axis, then produce various SAW resonators for comparison. The result proves that setting the IDT electrode pattern to satisfy the relation of $2 \times p \leq vb/f$ produces a similar advantage. Further, the metallization ratio η is set at approx. 0.5 and the normalized film thickness h/λ is set not less than 15%, then those preparation assures obtaining the SAW device having the foregoing advantages more positively. As a result, the yield rate can be substantially improved.

In the case of using the electrode made of aluminum or metal comprising mainly aluminum, and using piezoelectric substrate 1 comprising LN single-crystal and having a cut-face cut out at a rotation between not less than 50° and not more than 80° from Y-axis to Z-axis with respect to X-axis, various SAW resonators are also produced for comparison. The result proves that setting the IDT electrode pattern to satisfy the relation of $2 \times p \leq vb/f$ produces a similar advantage. Further, the metallization ratio η is set at approx. 0.5 and the normalized film thickness h/λ is set not less than 12%, then those preparations assure obtaining the SAW device having the foregoing advantages more positively. As a result, the yield rate can be substantially improved.

The present invention is not limited to the foregoing discussion. For instance, the electrode can use other materials than aluminum or metal mainly comprising aluminum. The piezoelectric substrate can use LT single-crystal or LN single-crystal cut out at another cut-angle, or it can use a substrate made of LiB_2O_3 (LBO), other materials for piezoelectric substrate or

piezoelectric thin-film. In such a case, the phase velocity of the SAW, which should have propagated as LSAW, can be reduced lower than the speed of the slow shear wave by using various means, so that the SAW can propagate as RSAW. At the same time, the film thickness and the shape of IDT electrode are set to satisfy the foregoing relation. Then a similar advantage to what is discussed above is achievable.

Exemplary Embodiment 2

A ladder SAW filter is produced as an example of the SAW device in accordance with the second exemplary embodiment of the present invention. Fig. 7A shows a perspective view illustrating a structure of this SAW filter. Fig. 7B shows a circuit diagram of this SAW filter. As Fig. 7B illustrates, the SAW filter comprises five SAW resonators 5 coupled in series, and two SAW resonators 6 coupled in parallel. Resonators 5 in series comprise IDT electrodes 7 and reflectors 9 disposed on both sides of electrodes 7. On the other hand, resonators 6 comprise IDT electrodes 8 and reflectors 10 disposed on both sides of electrodes 8. The film thickness and the pattern of the respective electrodes are set such that the center frequency becomes 836MHz and the bandwidth becomes 25MHz.

In this embodiment, LT substrate of 42° Y-cut and X-propagation (hereinafter referred to as LT42° substrate) is used as piezoelectric substrate 11. Slow shear wave propagating on this substrate 11 has a phase velocity v_b of 3350.8 m/s. Fig. 8 shows a relation between the normalized film thickness " h/λ " and a propagation loss of the SAW resonator that uses LSAW and is formed of piezoelectric substrate 11. The electrodes of the SAW resonator are made of Al-Cu alloy film where Cu is added to Al. A producing method of this SAW filter and an evaluating method of electrical

characteristics are similar to those in the first embodiment.

Table 2 shows the comparison between sample 2 and comparison sample 3 with respect to the following points: pitch "p" of finger-electrodes of IDT electrodes both of resonators 5 in series and resonators 6 in parallel, normalized film thickness " h/λ ", resonance frequency "f", and SAW phase velocity. Table 2 tells that sample 2 satisfies the relation of $2 \times p \leq v_b / f$, however, comparison sample 3 does not satisfy this relation. Fig. 9A shows the transmission characteristics of the SAW filter of sample 2, and Fig. 9B shows that of the SAW filter of comparison sample 3.

10 The indexes for evaluating respective transmission characteristics use the minimum insertion loss and a shape-factor of the filters. The shape factor is defined in the same way as disclosed in Japanese Patent Application Non-Examined Publication No. H09-167936. Fig. 10 describes the definition of the shape factor, to be more specific, it is defined in this way: Find
15 bandwidth BWb at point C2 where a signal is further attenuated by 1.5dB from the minimum insertion-loss point C1 of the pass-band, and find bandwidth BWa at point C3 where the signal is further attenuated by 20dB from point C1, and find the ratio as the shape factor, i.e., BW_a / BW_b . The characteristics of the filter becomes broader, a selection ratio degrades, and a
20 pass-band becomes narrower at a greater shape factor. Thus the shape factor becomes closer to 1 (one), and a pass-band filter becomes more sophisticated.

TABLE 2

	Resonator	Pitch between finger electrodes p (μm)	Normalized film thickness h/λ (%)	Resonance frequency f (MHz)
samples 2	(series arm) SAW resonators 5	1.81	19.3	835.9
	(parallel arm) SAW resonators 6	1.86	18.4	813.5
Comparison sample 3	(series arm) SAW resonators 5	2.4	9.9	836.3
	(parallel arm) SAW resonators 6	2.47	10.1	811.4
	Resonator	SAW velocity (m/s)	Minimum. insertion loss (dB)	shape factor (dB)
samples 2	(series arm) SAW resonators 5	3026.0	-2.1	1.4
	(parallel arm) SAW resonators 6	3026.2		
Comparison sample 3	(series arm) SAW resonators 5	4014.2	-2.8	1.5
	(parallel arm) SAW resonators 6	4008.3		

Table 2 shows the measurements of the minimum insertion loss and the shape factor of sample 2 and comparison sample 3. As table 2 tells, sample 2 obtains better results about the minimum insertion loss and the shape factor than comparison sample 3. The normalized film thickness h/λ of the SAW resonators of comparison sample 3 show values, as shown in Fig. 8, which make the propagation loss of LSAW on LT 42 substrate close to 0 (zero). On the other hand, the normalized film thickness h/λ of the SAW resonators of

sample 2 are 18.4% and 19.3%. Therefore, if the respective SAW resonators forming this SAW filter operate using the LSAW, the resonators incur greater propagation loss, as Fig. 8 shows. The minimum insertion loss and the shape factor should have become worse than those of comparison sample 3.

- 5 However, since the IDT electrodes are formed such that the respective SAW resonators satisfy the relation of $2 \times p \leq v_b / f$, sample 2 can achieve more sophisticated SAW filter than comparison sample 3.

In this second embodiment, a ladder SAW filter is used; however, the present invention is not limited to this filter. For instance, use of other
10 resonating SAW filters such as a lattice SAW filter, a multi-mode SAW filter, or IIDT (interdigitated interdigital transducer) SAW filter, also produces a similar advantage as far as they satisfy the relation of $2 \times p \leq v_b / f$.

The present invention achieves novel filter characteristics which prior art cannot obtain, so that a compact, light-weight and sophisticated filter is
15 obtainable. Use of this novel filter allows mobile communication apparatuses to be downsized and light-weighted.

Exemplary Embodiment 3

In this third embodiment, a 1-port SAW resonator similar to that used
20 in the first embodiment is used as a SAW device. Samples 3 – 6 employ LT 36 substrate as piezoelectric substrate 1, and a slow shear wave propagates on this LT 36 substrate at an phase velocity v_b of 3350.8 m/s. Comparison sample 4 employs LT 42 substrate as piezoelectric substrate 1. SAW resonators, of which structures are shown in Fig. 1A through Fig. 1C, are
25 formed on those piezoelectric substrates 1.

The SAW resonators of samples 3 – 5 have the following specification:
pitch “p” of finger-electrodes = 0.8 μ m, metallization ratio η = ca. 0.5,

resonance frequency " f " = 1890.6 MHz. Sample 6 has the following specification: " p " = 0.6 μm , η = ca. 0.5, " f " = 1890.6 MHz.

Samples 3 and 4 employ aluminum (Al) as the material of the electrodes of SAW resonators, and sample 3 has normalized film thickness h/λ = 19.8% while sample 4 uses thinner film of which h/λ is 15.0%. However, sample 4 is equipped with a step, on which electrodes are formed, on the LT substrate so that its resonance frequency agrees with that of sample 3. The way of forming the electrodes on the step is detailed later.

Sample 5 employs the electrodes made of tungsten (W) of which density is higher than Al, and has normalized film thickness h/λ of 2.7% because the difference in density is taken into account. Those preparations allow sample 5 to have the same resonance frequency as sample 3.

Sample 6 employs multi-layered film electrodes formed of W-layer and Al-layer as the electrodes of SAW resonator, and has normalized film thickness h/λ of 8.7%. Its resonance frequency is set at the same one as that of sample 3 because a thickness ratio of Al-layer vs. W-layer, and the difference in density of Al and W are taken into account. Those preparations allow the respective normalized film thickness h/λ of samples 4 – 6 to agree with that of sample 3 if they are converted into the case where Al is used.

The SAW resonator of comparison sample 4 is produced, which has the following specifications: " p " = 1.1 μm , η = ca. 0.5, and " h/λ " = ca. 10%. These specifications can minimize the insertion loss of LSAW in the case of using LT 42 substrate.

Samples 4 – 6 have the same resonance frequency " f ", i.e., 1890.6 MHz. The SAW resonators are produced and evaluated basically in the same way as those in the first embodiment. However, since sample 4 needs to form the step on the piezoelectric substrate, sputter-etching where Ar is added to

chlorine-based etching gas is carried out in the process of etching electrode-patterns of the IDT electrodes and resonator's electrodes. This sputter-etching etches exposed areas of the piezoelectric substrate, namely, partial spaces between the finger-electrodes, so that the step is formed. As a result,
5 the IDT finger-electrodes are formed in a given thickness on a top of the step having the same pitch as the IDT finger-electrodes.

In the case of samples 5 and 6, fluorine-based gas is used for etching the tungsten (W). Sample 6, in particular, uses chlorine-based gas for etching the Al-layer, and uses fluorine-based gas for etching the W-layer by using the
10 Al-layer as an etching mask.

The transmission characteristics of the SAW resonators of samples 3 – 6 and comparison sample 4 are shown in Fig. 11A – Fig. 11E respectively. Table 3 shows the characteristics measured of the respective SAW resonators.

The comparison of Fig. 11A – Fig. 11D of samples 3 – 6 with Fig. 11E of
15 comparison sample 4 proves that samples 3 – 6 have the better steep characteristics than comparison sample 4. Samples 3, 4, and 6 have less insertion-loss than comparison sample 4, to be more specific, the three samples have better numerical values about the min. insertion-loss and the index of insertion-loss than comparison sample 4. Sample 5, on the other
20 hand, results in rather inferior numerical values to comparison sample 4, because use of W in the IDT electrodes is obliged to reduce the film thickness, and W per se has a greater specific resistance than Al, so that the resistance of the IDT electrodes becomes greater.

TABLE 3

	Piezoelectric substrate	Pitch between finger electrodes p (μm)	Normalized film thickness h/λ (%)	Resonance frequency f (MHz)
Sample 3	36° LT substrate	0.8	19.8	1890.6
Sample 4	36° LT substrate	0.8	15.0	1890.6
Sample 5	36° LT substrate	0.8	2.7	1890.6
Sample 6	36° LT substrate	0.6	8.7	1890.6
comparison sample 4	42° LT substrate	1.1	10.0	1884.8
	Piezoelectric substrate	SAW velocity (m/s)	Insertion-loss index (dB)	Sharpness index
Sample 3	36° LT substrate	3025.0	-0.7	2202.4
Sample 4	36° LT substrate	3025.0	-0.7	2202.4
Sample 5	36° LT substrate	3025.0	-1.2	2202.4
Sample 6	36° LT substrate	2268.7	-0.3	2208.3
comparison sample 4	42° LT substrate	4146.6	-0.8	2089.2

Meanwhile, comparison sample 4 satisfies the specifications that can conventionally obtain a rather excellent SAW resonator: cut-angle of LT substrate = 42°, normalized film thickness of electrode $h/\lambda = \text{ca. } 10\%$. Samples 3 – 6, on the other hand, form the SAW resonators on the piezoelectric substrate cut out at an angle that allows the substrate to excite LSAW so that the relation of $2 \times p \leq v_b / f$ can be satisfied. The third embodiment thus proves that the SAW resonator having lower loss and similar or better steep characteristics than comparison sample 4 is obtainable with no substantial limits to a cut-angle of the substrate.

Comparison sample 4 is a SAW device having finger-electrodes made of Al and using LSAW. Film thickness "hL" of its IDT electrodes is $0.11\ \mu\text{m}$. Samples 3 and 4 also have the finger-electrodes of IDT electrodes made of Al, and approx. the same resonance frequency as that of comparison sample 4; however, they are SAW devices using the slow shear wave, and each one of them has film thickness "hL" of $0.32\ \mu\text{m}$ and $0.24\ \mu\text{m}$. Based on those results and measurements of other samples, it can be concluded that the structure satisfying $hL \leq h_r$ allows obtaining a SAW resonator of low loss and excellent steep characteristics without selecting a certain cut-angle. This is because the phase velocity of the SAW can be slower, due to mass-load effect, than that of the slow shear wave propagating on the piezoelectric substrate.

The comparison of transmission characteristics between samples 3 – 6 shown in Fig. 11A – Fig. 11D finds the following facts: Sample 3 shows some wavy characteristics, while samples 4 – 6 do not show such wavy phenomena. Because sample 3 makes an phase velocity of the wave, which should have propagated as LSAW, slower than that of the slow shear wave and uses the wave as RSAW, so that the reflection coefficient per electrode (IDT electrodes and reflector's electrodes) lowers. To overcome this problem, reconsidering the design is one way; however, it is necessary to improve the reflectance per electrode.

The comparison also finds the following facts about samples 4 – 6: Sample 4 shows smooth transmission characteristics because the step is provided. Samples 5 and 6 show also smooth transmission characteristics because entire or partial electrodes are made of W having the higher density than Al. Those facts tell that use of a step formed on a substrate, or use of electrodes entirely or partially made of material having higher density than aluminum is effective for improving the lowering of reflectance per electrode.

This lowering of reflectance is caused by the use of the wave as RSAW instead of LSAW by making the phase velocity slower than the slow shear wave.

In this third embodiment, formation of a step on a piezoelectric substrate or use of material having a higher density than aluminum improves
5 reflectance of the IDT electrodes and reflector's electrodes. There are other methods to improve the lowering of reflectance, e.g. formation of insulator between the IDT electrodes and the piezoelectric substrate to the extent that the electrical characteristics do not lower.

In this embodiment, tungsten (W) is selected as the material of higher
10 density than aluminum; however, the material of electrode is not limited to W, other metals such as Ta, Mo, Ti and Cu, or alloy of those metals or multi-layered film can be used. In the case of using the multi-layered film, it is not limited to the lamination structure or lamination materials discussed in this embodiment, but it can use various lamination structures satisfying the
15 condition of the present invention. The IDT electrodes and reflector's electrodes are not necessarily made of the same material, or do not always have the same structure.

At the same time, increase of a reflection coefficient of a bus-bar section forming both ends of SAW wave-guide area can reduce the leakage from the
20 wave-guide area, and improve the resonator's characteristics. However, it is preferable to moderately boost the resistance value of IDT electrodes in comparison with the case using aluminum in the electrodes, to be more specific, the resistance value is preferably not more than 10 times of the resistance value in the case of using aluminum. If the IDT electrodes have
25 rather high resistance, the material or the structure of the bus-bar other than IDT electrodes or wires routed is changed, thereby lowering the resistance of that section. This method is particularly effective when the SAW filter using

the resonator discussed in this third embodiment is formed.

Use of electrode material, such as W or Mo, having a smaller coefficient of linear thermal expansion than the substrate material, or use of the laminated electrode using the foregoing electrode materials can improve not only the reflectance but also temperature characteristics. On top of that, the present invention allows the film thickness of the electrodes to be thicker than that of the conventional SAW, thus the greater effect can be expected.

Exemplary Embodiment 4

The fourth embodiment uses a 1-port SAW resonator similar to the one used in the first embodiment. Samples 7 and 8 for this fourth embodiment use Al as the material of IDT electrodes 3 and reflector's electrodes 4 both formed on piezoelectric substrate 1 which employs LT 36 substrate. The slow shear wave propagates on substrate 1 at phase velocity v_b of 3350.8 m/s.

Samples 7 and 8, as shown in Figs. 12A and 12B, have dielectric film for covering IDT electrodes and reflectors of the SAW resonators.

Sample 7 uses silicon-nitride film 12 as this dielectric film. Fig. 12A shows the sectional view of this structure, where finger-electrodes 301 of the IDT electrodes are formed on piezoelectric substrate 1, and silicon-nitride film 12 is formed as the dielectric film over finger-electrodes 301 and substrate 1.

Sample 8 uses silicon-oxide film 13 as the dielectric film. Fig. 12B shows the sectional view of this structure, where finger-electrodes 301 of the IDT electrodes are formed on piezoelectric substrate 1, and similar to the structure shown in Fig. 12A, silicon-oxide film 13 is formed as the dielectric film over electrodes 301 and substrate 1. Characteristics of the respective SAW resonators are shown in Table 4.

Sample 7 has the following specifications: pitch "p" of finger-electrodes

= $0.80 \mu\text{m}$, metallization ratio $\eta = \text{ca. } 0.5$, resonance frequency before silicon-nitride film 12 is formed " f_{before} " = 1885.45 MHz, and resonance frequency after film 12 is formed " f_{after} " = 1876.30 MHz. In sample 7, the phase velocity of the SAW before film 12 is formed is 3016.7 m/s, which is
 5 slower than that of the slow shear wave. Thus the relation of $2 \times p \leq v_b / f_{\text{before}}$ can be satisfied. Further, the phase velocity of the SAW after film 12 is formed is 3002.1 m/s, which is also slower than that (3350.8 m/s) of the slow shear wave. Then the relation of $2 \times p \leq v_b / f_{\text{after}}$ can be satisfied. In other words, sample 7 satisfies the relation of $2 \times p \leq v_b / f$ both before and after
 10 film 12 is formed.

Sample 8 has the following specification: " p " = $0.80 \mu\text{m}$, $\eta = \text{ca. } 0.5$, resonance frequency before silicon-oxide film 13 is formed " f_{before} " = 1848.37 MHz, and resonance frequency after film 13 is formed " f_{after} " = 2484.20 MHz. In sample 8, the phase velocity of the SAW before film 13 is formed is 2957.4
 15 m/s, which is slower than that of the slow shear wave. Thus the relation of $2 \times p \leq v_b / f_{\text{before}}$ can be satisfied. Further, the phase velocity of the SAW after film 13 is formed is 3974.7 m/s, which is faster than that (3350.8 m/s) of the slow shear wave. Then the relation of $2 \times p \geq v_b / f_{\text{after}}$ can be satisfied. In other words, sample 8 satisfies the relation of $2 \times p \times f_{\text{before}} \leq v_b \leq 2 \times p \times f_{\text{after}}$ both before and after film 13 is formed.
 20

Comparison samples 5 and 6 are produced to use SAW resonators employing regular LSAWs of which resonance frequencies are equal to f_{after} of samples 7 and 8 respectively. Both comparison samples 5 and 6 employ electrodes made of Al in the SAW resonators, and use 36 Y-cut and X-propagation LT substrate as piezoelectric substrate. Comparison sample 5
 25 has the following specifications: pitch " p " of electrodes = $1.06 \mu\text{m}$, metallization ratio $\eta = \text{ca. } 0.5$, and comparison sample 6 has pitch " p " of

electrodes = $0.81 \mu\text{m}$, metallization ratio $\eta = \text{ca. } 0.5$. According to equation (1), the acoustic velocities of LSAW of comparison samples 5 and 6 are thus calculated as 4001.3 m/s and 4004.3 m/s respectively. They are faster than that of the slow shear wave.

5 Figs. 13A and 13B show transmission characteristics of sample 7 before and after dielectric film 12 is formed. Figs. 14A and 14B show transmission characteristics of sample 8 before and after dielectric film 13 is formed. Figs. 15 and 16 show transmission characteristics of comparison samples 5 and 6 respectively.

10 Those SAW resonators discussed above are basically produced in the same way and evaluated in the same manner as the first embodiment. The dielectric films of samples 7 and 8 are formed in the following way: First, form the electrode-pattern, then form the dielectric film on the entire wafer by sputtering, and remove the dielectric film only from a pad-area, where a
15 probing device needs to contact for measuring the electrical characteristics, by photo-lithography and etching. The characteristics of those samples are shown in Table 4.

TABLE 4

	Piezoelectric substrate	Pitch between finger electrodes p (μm)		without dielectric film	
				Resonance frequency f (MHz)	SAW velocity (m/s)
sample 7	36 LT substrate	0.8		1885.5	3016.7
sample 8	36 LT substrate	0.8		1848.4	2957.4
Comparison sample 5	36 LT substrate	1.06		1880.3	4001.3
Comparison sample 6	36 LT substrate	0.81		2465.7	4004.3
	Piezoelectric substrate	Insertion loss index (dB)	Sharpness index	with dielectric film	
				Resonance frequency f (MHz)	SAW velocity (m/s)
sample 7	36 LT substrate	-1	2465.9	1876.3	3002.1
sample 8	36 LT substrate	-1.1	2191.7	2484.2	3974.7
Comparison sample 5	36 LT substrate	-2.6	2053.3	—	—
Comparison sample 6	36 LT substrate	-2.8	2097.7	—	—

As Figs. 13A and 13B illustrate, sample 7 obtains improved insertion-loss and steep characteristics after silicon-nitride film 12. In comparison with comparison sample 5 shown in Fig. 15, sample 7 has insertion-loss and steep characteristics rather inferior to those of comparison sample 5 before film 12 is formed. However, after film 12 is formed, sample 7 gets better characteristics than those of comparison sample 5. This experiment proves that the advantage of the present invention can be obtained after the dielectric film such as silicon-nitride film 12 is formed.

Sample 8 shows an increase of the resonance frequency after silicon-oxide film 13 is formed. As the comparison of Fig. 14A with Fig. 14B tells,

there are no substantial changes in the insertion-loss or the steep characteristics. In comparison with comparison sample 6 shown in Fig. 16, sample 8 shows better characteristics than a SAW resonator using regular LSAW both before and after the dielectric film is formed.

5 When the phase velocity of SAW increases due to forming of the dielectric film such as silicon-oxide film 13, pitch "p" and resonance frequency f_{before} are adjusted so that the relation of $2 \times p \times f_{\text{before}} \leq v_b \leq 2 \times p \times f_{\text{after}}$ is satisfied, then a SAW resonator excellent in the insertion-loss and the steep characteristics is obtainable. In general, pitch "p" of a SAW resonator
10 becomes wider at a lower frequency, therefore, in the foregoing case, the increase of SAW's phase velocity due to the dielectric film can be used for widening the pitch "p" of the SAW resonator. This is the advantage of manufacturing SAW devices.

Use of silicon-nitride film as the dielectric film decreases the resonance
15 frequency, however, a degree of the decrease can be adjusted with the film thickness. Comparison sample 6 having the phase velocity of 4004.3 m/s before the dielectric film is formed. The silicon-nitride film thicker than that of sample 7 is formed on the surface of SAW resonator, of which phase velocity is faster than that of the slow shear wave, then reduction of resonance
20 frequency can be expected after the film is formed. Selection of an appropriate film thickness can satisfy the relation of $2 \times p \times f_{\text{after}} \leq v_b$, and obtains the advantage of the present invention.

In this fourth embodiment, silicon-nitride film or silicon-oxide film is used as dielectric film; however, the present invention is not limited to those
25 materials. For instance, a film laminated of polyimide-based resin or silicon-nitride film, and silicon-oxide film can be used. Further, in this embodiment, the dielectric film is provided on the upper face of IDT

electrodes; however, the dielectric film can be formed directly on the piezoelectric substrate, and the IDT electrodes are formed thereon, or they can be combined. Those methods also produce a similar advantage to what is discussed above.

5 A change in phase velocity due to forming of the dielectric film depends on a material of the film, a film thickness, and a structure of the film. There is thus an optimum condition for each one of those factors to produce SAW devices according to actual cases.

10 Exemplary Embodiment 5

The SAW device in accordance with the fifth embodiment of the present invention includes a ladder SAW filter working in 800 MHz band and a ladder SAW filter working in 1.9 GHz band, where both filters are formed on one chip, i.e. a filter of two-filters in one-chip. In this embodiment, four samples are
15 produced, namely, samples 9 and 10, and comparison samples 7 and 8. A transmitting filter for AMPS/CDMA in the US is used as an 800 MHz band filter, and a transmitting filter for CDMA in PCS band in the US is used as a 1.9 GHz band filter.

The transmitting filter in 800 MHz band needs the following
20 specifications: pass-band = 824 – 849 MHz; insertion-loss $\leq$ 2.5 dB, rejection band in receiving band = 869 – 894 MHz; and degree of attenuation $\geq$ 40 dB. On the other hand the transmitting filter in 1.9 GHz band needs the following specification (requested specifications): pass-band = 1850 – 1910 MHz; insertion-loss $\leq$ 2.5 dB, rejection band in receiving band = 1930 – 1990 MHz;
25 and degree of attenuation $\geq$ 40 dB.

In sample 9, Al-film is formed on 39 LT substrate, and ladder SAW filters for 800 MHz band and 1.9 GHz band are produced by photo-lithograph

and etching methods. The SAW resonator of this 800 MHz filter has IDT electrodes of which normalized film-thickness h/λ is ca. 6.0%, so that this SAW resonator has the specification agreeing with the condition that the SAW resonator employing 39 LT substrate and using LSAW incurs propagation-
 5 loss of almost 0 (zero). The SAW resonator forming this 800MHz SAW filter uses LSAW, and its relation between resonance frequency and pitch of electrodes does not satisfy the relation of $2 \times p \leq v_b/f$.

The ladder SAW filter for 1.9GHz includes a SAW resonator, of which resonance frequency "f" and pitch "p" of electrodes are designed such that the
 10 relation of $2 \times p \leq v_b/f$ is satisfied, thus the phase velocity of LSAW is lowered and the LSAW is used as RSAW.

In sample 10, W and Al are layered in this order on 39 LT substrate, then patterns of ladder SAW filters for 800MHz and 1.9GHz are formed thereon by photo-lithography and etching methods. In this case, first the Al
 15 layer is etched by Cl-based gas as dry-etching gas, then the W layer is etched by F-based gas without exposing the layers to the atmosphere. Next, a resist is removed, then a filter pattern of 800MHz filter is protected by the resist, and the Al layer of a filter pattern of 1.9GHz filter is etched by Cl-based gas again. As a result, the IDT electrodes of 800MHz filter are formed of two
 20 layers, i.e. W layer and Al layer, and those of 1.9GHz filter are formed of single layer, i.e. W layer.

The SAW resonator of this 800MHz SAW filter of sample 10 uses LSAW and its resonance frequency "f" as well as pitch "p" of electrodes does not satisfy the relation of $2 \times p \leq v_b/f$. The SAW resonator of the ladder SAW
 25 filter for 1.9GHz band is designed such that resonance frequency "f" and pitch "p" satisfy the relation of $2 \times p \leq v_b/f$. This 1.9GHz filter thus uses LSAW as RSAW by lowering the phase velocity of the LSAW.

In comparison sample 7, first, form Al-film, of which thickness corresponds to that of the 1.9GHz filter, on 39 LT substrate, second, protect the filter section of 1.9GHz with resist, then form Ti-film and Al-film in this order to make the film-thickness to be that of a 800MHz filter. In this case, the Ti-film is used as an adhering layer. The resist protecting the filter section of 1.9GHz band is removed together with Ti-film and Al-film attached to the filter section. Then apply resist for protecting the filter section of 1.9GHz band and forming the pattern of 800MHz filter. Expose the resist to light, then provide the resist with dry-etching, thereby producing a filter for 800MHz band and a filter for 1.9GHz band on one chip.

The SAW resonators of 800MHz filter and 1.9GHz filter in comparison-sample 7 use LSAW, and the relation between resonance frequency "f" and pitch "p" does not satisfy the relation of $2 \times p \leq v_b/f$.

In comparison sample 8, Al and W are layered in this order on 39 LT substrate, then patterns of ladder SAW filters for 800MHz and 1.9GHz are formed thereon by photo-lithography and etching methods. In this case, first the W layer is etched by F-based gas as dry-etching gas, then the W layer is etched by Cl-based gas without exposing the layers to the atmosphere. Next, a resist is removed, then a filter pattern of 800MHz filter is protected by the resist again, and the W layer of a filter pattern of 1.9GHz filter is etched by F-based gas. As a result, the IDT electrodes of 1.9GHz filter are formed of single layer, i.e. W layer, and those of 800MHz filter are formed of two layers, i.e. W layer and Al layer.

The SAW resonators of 800MHz filter and 1.9GHz filter in comparison sample 8 both use LSAW, and their frequency "f" and pitch "p" do not satisfy the relation of $2 \times p \leq v_b/f$.

For samples 9 and 10, and comparison samples 7 and 8, after the

patterns of IDT electrodes are formed, Al-film is vapor-deposited for reinforcing purpose on the wiring routed, bus-bars, and pad sections. Then those wafers are diced into pieces of chips, which are then die-bonded on ceramic-packages of 3mm square. They are electrically connected with wire-
5 bonding, and air-tightly sealed in nitrogen atmosphere.

Figs. 17A and 17B show the transmission characteristics of sample 9, Figs. 18A and 18B show that of sample 10, Figs. 19A and 19B show that of comparison sample 7, and Figs. 20A and 20B show the transmission characteristics of comparison sample 8. Each drawing also shows the
10 respective pass-band (transmitting band) and rejection band (receiving band).

A detailed observation of those results proves that samples 9, 10 and comparison samples 7, 8 obtain the characteristics substantially equal to each other on the 800MHz SAW filters. Samples 9 and 10 satisfy the requested specifications of 1.9GHz SAW filters by lowering the phase velocity of the
15 wave, which should have propagated as LSAW, for using the wave as RSAW. On the other hand, comparison samples 7 and 8 do not satisfy the requested specifications in respect of the insertion-loss and the degree of attenuation in rejection-band of the pass-band. Comparison of sample 9 with sample 10 tells that sample 10 has almost no ripples which sample 9 has, which seems to
20 be caused by the IDT electrodes made of W.

Although the electrodes of sample 10 are made of only W, sample 10 has the insertion-loss similar to those of other samples. Because the IDT electrodes of the SAW resonator hardly affects the loss, and the wiring routed is reinforced with Al. Comparison sample 7 finally obtains characteristics on
25 only few items because of its complicated production process, and results in a poor yield.

Exemplary Embodiment 6

A sensor employing the SAW device of the present invention is demonstrated hereinafter with reference to accompanying drawings.

A temperature sensor is taken as an instance of the sensor employing the SAW device. Fig. 21 shows a schematic diagram illustrating a basic structure of this sensor. In Fig. 21, packaged SAW resonator 22 is mounted to a tip of insulating member 21, and an output section of resonator 22 is electrically coupled to network analyzer 24 via wires 23 disposed on insulating member 21. This temperature sensor uses SAW resonator 22 as its sensing section, and analyzer 24 measures the transmission characteristics of resonator 22.

SAW resonator 22 changes its frequency characteristics in response to an ambient temperature, and this temperature sensor can thus measure the temperature using a change in the frequency. In this sixth embodiment, a movement of anti-resonance frequency due to a change in temperature is monitored.

The SAW resonator used in sample 1 described in the first embodiment is used as SAW resonator 22. Sensor 1 equipped with this SAW resonator and a comparison sensor equipped with the SAW resonator used in comparison sample 1 in the first embodiment are used here.

The characteristics of those two sensors are evaluated in the following manner: Put the sensing section, i.e. SAW resonator 22, into an oven, and find a relation between a variation in the ambient temperature and a variation in the anti-resonance frequency with the ambient temperature varying. The resultant relation is shown in Fig. 22, in which the vertical axis shows a variation in the anti-resonance frequencies and the horizontal axis shows a difference in temperature from room temperature (25°C). The result

proves that the temperature characteristics of sensor 1 is ca. 130 ppm/K, while that of the comparison sensor is 35 ppm/K. Figs. 3A and 3B used in the first embodiment also tell that the characteristics of sensor 1 around the anti-resonance frequency is sharper than that of the comparison sensor. It can be thus concluded that sensor 1 can measure a temperature more sensitive than the comparison sensor.

The temperature characteristics discussed above takes advantage of the fact that temperature characteristics of a substrate can be changed by thickening a film-thickness of IDT electrodes. In this case, when the electrodes made of Al are used, the IDT electrodes preferably have normalized film thickness h/λ of not less than 10%.

Industrial Applicability

The present invention lowers the phase velocity of LSAW to not more than that of the slow shear wave propagating on a piezoelectric substrate, so that bulk-wave is prevented from radiating for reducing the loss of a SAW device such as a SAW resonator or a SAW filter. At the same time, the steep characteristics of the SAW device can be increased.

CLAIMS

1. A surface acoustic wave (SAW) device comprising:
 - a piezoelectric substrate cut out at a cut-angle allowing the
 - 5 substrate to excite a leaky surface acoustic wave (LSAW); and
 - an electrode pattern formed of an inter-digital transducer (IDT) electrode prepared on said substrate, the IDT electrode having at least a pair of finger-electrodes meshing with each other,
 - wherein a pitch p (m) of the finger-electrodes satisfies a relation
 - 10 of $2 \times p \leq v_b/f$,
 - where v_b (m/s) is an phase velocity of a slow shear wave propagating on said substrate, and f (Hz) is a resonance frequency of the SAW device.
2. The SAW device of claim 1, wherein the finger-electrodes of said
- 15 electrode pattern are formed on a top of a step prepared on said substrate, the step having a pitch similar to the pitch p .
3. The SAW device of claim 1 further comprising a dielectric film
- disposed over said electrode pattern for covering at least said electrode
- 20 pattern.
4. A surface acoustic wave (SAW) device comprising:
 - a piezoelectric substrate cut out at a cut-angle allowing the
 - substrate to excite a leaky surface acoustic wave (LSAW);
 - 25 an electrode pattern formed of an inter-digital transducer (IDT) electrode prepared on said substrate, the IDT electrode having at least a pair of finger-electrodes meshing with each other; and

a dielectric film disposed over said electrode pattern for covering at least said electrode pattern,

wherein a pitch p (m) of the finger-electrodes satisfies a relation of $2 \times p \times f_{\text{before}} \leq vb \leq 2 \times p \times f_{\text{after}}$,

5 where f_{before} (Hz) is a resonance frequency of the SAW device before said dielectric film is formed, f_{after} (Hz) is that of after said dielectric film is formed, and vb (m/s) is a phase velocity of a slow shear wave propagating on said substrate.

10 5. The SAW device of any one of claim 1 through claim 4, wherein the finger-electrodes are made of one of aluminum (Al) and metal comprising mainly Al, and a relation of $hL \leq hr$ is satisfied, where hL is a film thickness of an IDT electrode of another SAW device using the LSAW and said piezoelectric substrate, and hr is a film thickness of the
15 IDT electrode of the SAW device of which resonance frequency is set at identical to that of the another SAW device.

6. The SAW device of any one of claim 1 through claim 4, wherein at least the finger-electrodes are made of metal having a larger density than Al.

20 7. The SAW device of any one of claim 1 through claim 4, wherein at least the finger-electrodes are formed of at least two layers, namely, a first layer is made of Al, and a second layer is formed of one of Al and metal comprising mainly Al, where the metal has a greater density than Al.

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8. The SAW device of any one of claim 1 through claim 4, wherein said substrate is made of single crystal of LiTaO_3 .

9. The SAW device of claim 5, wherein said substrate is made of single crystal of LiTaO_3 .

5 10. The SAW device of claim 6, wherein said substrate is made of single crystal of LiTaO_3 .

11. The SAW device of claim 7, wherein said substrate is made of single crystal of LiTaO_3 .

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12. The SAW device of claim 8, wherein said substrate made of single crystal of LiTaO_3 having a cut-face cut out at a rotation angle ranging between not less than 26 and not more than 50 from Y-axis to Z-axis with respect to X-axis of the single-crystal of LiTaO_3 , and said substrate allows exciting the
15 LSAW.

13. The SAW device of claim 9, wherein said substrate made of single crystal of LiTaO_3 having a cut-face cut out at a rotation angle ranging between not less than 26 and not more than 50 from Y-axis to Z-axis with respect
20 to X-axis of the single-crystal of LiTaO_3 , and said substrate allows exciting the LSAW.

14. The SAW device of claim 10, wherein said substrate made of single crystal of LiTaO_3 having a cut-face cut out at a rotation angle ranging between
25 not less than 26 and not more than 50 from Y-axis to Z-axis with respect to X-axis of the single-crystal of LiTaO_3 , and said substrate allows exciting the LSAW.

15. The SAW device of claim 11, wherein said substrate made of single crystal of LiTaO_3 having a cut-face cut out at a rotation angle ranging between not less than 26° and not more than 50° from Y-axis to Z-axis with respect to X-axis of the single-crystal of LiTaO_3 , and said substrate allows exciting the LSAW.

16. The SAW device of any one of claim 1 through claim 4, wherein said substrate is made of single crystal of LiNbO_3 .

17. The SAW device of claim 5, wherein said substrate is made of single crystal of LiNbO_3 .

18. The SAW device of claim 6, wherein said substrate is made of single crystal of LiNbO_3 .

19. The SAW device of claim 7, wherein said substrate is made of single crystal of LiNbO_3 .

20. The SAW device of claim 16, wherein said substrate made of single crystal of LiNbO_3 having a cut-face cut out at a rotation angle ranging from not less than 50° to not more than 80° with respect to X-axis of the single-crystal of LiNbO_3 , and said substrate allows exciting the LSAW.

21. The SAW device of claim 17, wherein said substrate made of single crystal of LiNbO_3 having a cut-face cut out at a rotation angle ranging from not less than 50° to not more than 80° with respect to X-axis of the single-

crystal of LiNbO_3 , and said substrate allows exciting the LSAW.

22. The SAW device of claim 18, wherein said substrate made of single crystal of LiNbO_3 having a cut-face cut out at a rotation angle ranging from
5 not less than 50 to not more than 80 with respect to X-axis of the single-crystal of LiNbO_3 , and said substrate allows exciting the LSAW.

23. The SAW device of claim 19, wherein said substrate made of single crystal of LiNbO_3 having a cut-face cut out at a rotation angle ranging from
10 not less than 50 to not more than 80 with respect to X-axis of the single-crystal of LiNbO_3 , and said substrate allows exciting the LSAW.

24. A surface acoustic wave (SAW) device comprising at least two SAW devices, as defined in any one of claim 1 through claim 4, combined to each
15 other and formed on one chip.

25. A mobile communication apparatus employing the SAW device as defined in any one of claim 1 through claim 4.

20 26. A mobile communication apparatus employing the SAW device as defined in claim 24.

27. A sensor employing the SAW device as defined in any one of claim 1 through claim 4.

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28. A method of designing a surface acoustic wave (SAW) device which comprises:

a piezoelectric substrate cut out at a cut-angle allowing the substrate to excite a leaky surface acoustic wave (LSAW); and

an electrode pattern formed of an inter-digital transducer (IDT) electrode prepared on said substrate, the IDT electrode having at least a pair of finer-electrodes meshing with each other,

the method determining said electrode pattern and the cut-angle to satisfy a relation of

$$2 \times p \leq v_b / f,$$

where p (m) is a pitch of the finger-electrodes of said electrode pattern, v_b (m/s) is a phase velocity of a slow shear wave propagating on said substrate, and f (Hz) is a resonance frequency of the SAW device.

29. A method of designing a surface acoustic wave (SAW) device which comprises:

a piezoelectric substrate cut out at a cut-angle allowing the substrate to excite a leaky surface acoustic wave (LSAW);

an electrode pattern formed of an inter-digital transducer (IDT) electrode prepared on said substrate, the IDT electrode having at least a pair of finger-electrodes meshing with each other; and

a dielectric film disposed over said electrode pattern for covering at least said electrode pattern,

the method determining said electrode pattern, the cut-angle and material of said dielectric film to satisfy a relation of

$$2 \times p \times f_{\text{before}} \leq v_b \leq 2 \times p \times f_{\text{after}},$$

where f_{before} (Hz) is a resonance frequency of the SAW device before said dielectric film is formed, f_{after} (Hz) is that of after said dielectric film is formed, p (m) is a pitch of the finger-electrodes of said electrode pattern, v_b (m/s) is an

phase velocity of a slow shear wave propagating on said substrate.

30. A method of designing the SAW device as defined in claim 28 or claim 29, wherein the electrodes of the SAW device are made of one of
5 aluminum (Al) and metal comprising mainly Al, the method determining said electrode pattern and the cut-angle to satisfy a relation of $h_L \leq h_r$,
where h_L is a film thickness of an IDT electrode of another SAW device using the LSAW and said piezoelectric substrate, and h_r is a film thickness of the IDT electrode of the SAW device of which resonance frequency is set at
10 identical to that of the another SAW device.