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Surface Acoustic Wave Properties of Zinc Oxide Film on Quartz Substrate

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SUMMARY

Substrates for surface acoustic wave (SAW) devices having various characteristics are realized by combining piezoelectric zinc oxide (ZnO) film and various substrates. This paper reports the following results: (1) the author realized Rayleigh SAW substrates having an appropriate electromechanical coupling factor ($k_s^2 = 0.01$—seven times that of ST-cut X-propagation quartz), a good temperature coefficient of frequency (TCF ≃ 1 ppm/°C), and a zero power flow angle by combining ZnO film and an ST-cut 35° X-propagation quartz substrate, and (2) the author realized a high mode of leaky SAW substrates having a high velocity and a good TCF (≃ 1 ppm/°C) by combining the ZnO film and an ST-cut 90° X-propagation quartz substrate. © 2000 Scripta Technica, Electron Comm Jpn Pt 2, 83(10): 1–9, 2000

Key words: ZnO film; quartz; Rayleigh wave; high mode of leaky SAW; TCF; electromechanical coupling factor; temperature coefficient of frequency.

1. Introduction

Surface acoustic wave (SAW) filters have been widely applied as key parts of mobile telecommunications and other systems. There are several kinds of SAW filters, such as transversal, resonator-type, and ladder-type filters. These filters must have small size, low cost, low loss, an excellent temperature coefficient of frequency (TCF), and a bandwidth corresponding to the usage. For SAW filters in the low-frequency range, a substrate having low velocity is preferable for achieving miniaturization. In contrast, for SAW filters in the high-frequency range, a substrate having high velocity is preferable for the formation of fine-pitch interdigital transducer (IDT) electrodes. A substrate having a suitable electromechanical coupling factor (k_s) is required for applications of SAW filters such as resonator-type SAW, rudder-type SAW, or other filters requiring a specific bandwidth, because their bandwidth greatly depends on the coupling factor of the substrate. In general, it is desired that the TCF of the substrate be excellent, and it is necessary for SAW filters requiring a narrow bandwidth. An ST-cut X-propagation quartz substrate for Rayleigh SAW devices is known for its good TCF; however, its k_s can be as small as 0.037 (or 0.0014 at k_s^2), so it is often unsuitable for application to SAW devices requiring a specific bandwidth. Although a langasite single crystal having a larger coupling factor ($k_s^2 = 0.0046$) than that of quartz and a similar TCF value (1.55 ppm/°C) to quartz has attracted much attention in recent years [1], a substrate having a larger coupling factor is desired. The velocity of the Sezawa wave on the combined ZnO film and sapphire substrate is high, but the TCF is poor. A single-crystal substrate has peculiar constant values of the TCF, the velocity, and the coupling factor which depend on the type of substrate. The combination of a ZnO film and a substrate has different values according to the type of substrate. The author attempts to realize the following two types of SAW substrates having specific advantages by combining ZnO films and specific-angle quartz substrates:

(1) a substrate having an excellent TCF and an appropriate large coupling factor;

(2) a substrate having an excellent TCF and high velocity.

Generally, most single crystals and thin films have a negative TCF. Only a few materials, such as a quartz substrate having a specific cut angle or propagation direction and a SiO_2 film, have a positive TCF. Many investigations in which the initially negative TCF of $LiNbO_3$ and $LiTaO_3$ substrates was improved by depositing a SiO_2 film having a positive TCF have been reported [1–3]. However, since the absolute value of the TCF of such substrates is large, a relatively thick film of SiO_2 is required to compensate its negative TCF. For example, the normalized SiO_2 thickness H/λ is 0.4 in the case of SiO_2/YZ-$LiNbO_3$, and 0.5 in the case of SiO_2/YZ-$LiTaO_3$, where H is the SiO_2 thickness and λ is the wavelength of the SAW [1]. In the case of SAW devices requiring a specific bandwidth, their coupling factor is often not suitable (often too large).

In the case of a quartz substrate, not only a positive TCF but also a negative TCF can be obtained by selecting an appropriate cut angle or propagation direction. The author has studied the opposite combination, that is, a combination of a specific quartz substrate having a positive TCF with a ZnO film having a negative TCF. Experimental results on a combination of the X-cut 25° propagation quartz substrate and the ZnO film were previously reported [4]. However, the quartz substrate having this cut angle and propagation is not used in practice because the power flow angle (PFA) is not zero, an excellent TCF has not been obtained experimentally, and its k_s has not been reported [4]. The author attempted to realize SAW properties of the combination of a ZnO film having a negative TCF and a quartz substrate having an appropriate positive TCF (+10 to +25 ppm/°C) and PFA = 0 theoretically and experimentally. A SAW substrate having a good TCF, zero PFA, and an appropriate electromechanical coupling factor was realized both theoretically and experimentally [5, 6]. Moreover, the characteristics of the filter employed in this combination are reported.

The author attempted to realize a SAW substrate having an excellent TCF and a high velocity by combining ZnO film and a specific-cut-angle quartz substrate having a high velocity. The Rayleigh SAW (Rayleigh 0th) and its higher modes [Rayleigh 1st (Sezawa SAW), 2nd, . . .] are generated by combining a ZnO film and a nonpiezoelectric substrate having a high velocity. Not only the Rayleigh SAW but also a leaky SAW (LSAW) are generated on a piezoelectric substrate. The Rayleigh SAW velocities on the quartz substrates are low, but the LSAW velocities on specific-cut-angle quartz substrates are high. It is considered that the fundamental LSAW and its higher modes having a high velocity and good TCF are generated as well as the Rayleigh SAW and its higher modes by combining a ZnO film and a quartz substrate having a high LSAW velocity and an appropriate positive TCF. The author reported this result in Refs. 7 and 8 in 1995 [9]. Only calculated values of velocity and propagation losses of LSAW and its higher modes on a ZnO/ST-cut X-propagation quartz substrate, which is different from the author's reported propagation direction, were presented at the IEEE Ultrasonic Symposium in 1998 [10]. Because this ST-X quartz substrate has a negative TCF of the LSAW, it is not suitable for achieving the desired TCF of ZnO/quartz LSAW devices. Reference 10 did not report the calculated k_s or TCF values, nor any experimental results. In this paper, the author reports the calculated and measured LSAW properties of combinations of the ZnO film and quartz substrate.

2. Substrates for Rayleigh SAW Having Good TCF and Appropriate Coupling Factor

2.1. Quartz substrates having positive TCF

–90°-rotated Y-plate X-propagation to 35°-rotated Y-plate X-propagation quartz substrates [substrates between (0°, 0°, 0°) and (0°, 125°, 0°) at Euler angle] generate a Rayleigh SAW with a positive TCF [11]. It is expected that a zero TCF will be realized if a thin film having a negative TCF is deposited on this positive-TCF substrate. However, since quartz substrates with these cut angles are not readily available, the author used ST-cut quartz substrates which are readily available, and selected a 29°45′-rotated Y plate and a 42°45′-rotated Y plate for this experiment. The Euler angles are expressed as (0°, 119°45′, ψ) and (0°, 132°45′, ψ). Since the TCF of an X-propagation Rayleigh SAW of these ST-cut quartz substrates is almost zero, the dependence of the phase velocity, the TCF, and the coupling factor k_s on the propagation direction from the X-axis was calculated so as to obtain the preferred positive TCF and a zero PFA. The phase velocity was calculated by the method developed by Campbell and Jones [12]. The coupling factor k_s was calculated from the difference in velocity $[(V_f - V_m)/V_f]$: V_f and V_m are the velocities when the plane of the IDT is electrically open and shorted, respectively. The TCF was calculated by substituting the velocity V calculated for 15, 25, and 35 °C into the following equation:

$$\mathrm{TCF} = [V(35\ °\mathrm{C}) - V(15\ °\mathrm{C})]/[20 \times V(25\ °\mathrm{C})] - \alpha \quad (1)$$

where α is the linear expansion coefficient.

The dependences of TCF and PFA on the SAW propagation direction ψ (ψ is the angle between the propagation direction and the X-axis) are shown in Fig. 1. The respective dependences of the velocity and k_s of Rayleigh

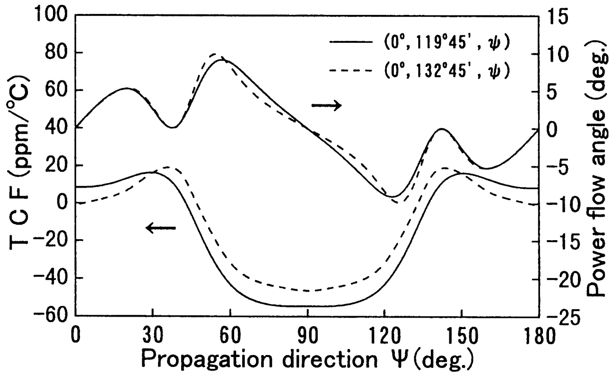

Fig. 1. Propagation direction dependence of TCF and PFA in Rayleigh SAW on ST-quartz.

SAW and the velocity of LSAW on the propagation direction are shown in Fig. 2. The solid and dashed lines in these figures indicate the values calculated for the 29°45′- and 42°45′-rotated Y-plate quartz substrates, respectively. The LSAW in Fig. 2 will be discussed later. For both substrates, a preferred positive TCF (+15 to +20 ppm/°C) and a zero PFA are obtained at a propagation direction in the vicinity of 35° from the X-axis. In addition, almost the same coupling factor value as that of X-propagation is observed [5, 6]. Thus, the author investigates SAW properties for the combination of ZnO films and quartz substrates in this propagation direction, that is, the 29°45′- and 42°45′-rotated Y–35° X-propagation quartz substrates (29°45′-rotated Y–35° X and 42°45′-rotated Y–35° X quartz). The Euler angles are expressed as (0°, 119°45′, 35°) and (0°, 132°45′, 35°).

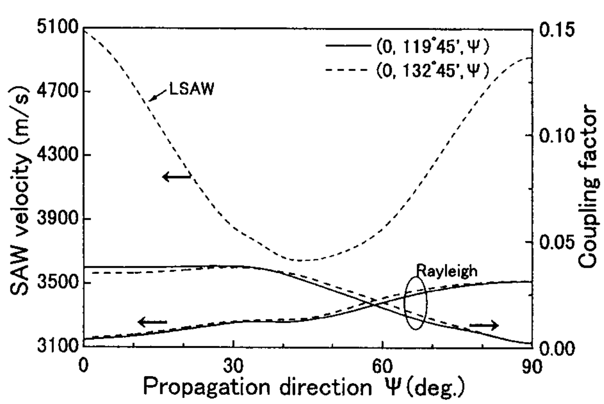

Fig. 2. Propagation direction dependence of calculated velocity and electromechanical coupling factor on ST-quartz.

2.2. Electromechanical coupling factor of ZnO/quartz

There are four combinations for a piezoelectric film ZnO/substrate structure according to the positions of the IDT electrodes and the shorted plane. The k_s values of Rayleigh and Sezawa SAWs in IDT/ZnO/quartz (29°45′-rotated Y–35° X) and IDT/ZnO/shorted-plane/quartz structures were calculated. In Fig. 3, the calculated results of Rayleigh and Sezawa SAWs are shown by solid and dashed lines, respectively, as a function of the ZnO film thickness. The IDT/ZnO/quartz structure has a large Rayleigh SAW coupling factor (0.1) in the range of $H/\lambda \geq 0.2$. Its k_s^2 value is about seven times that of the Rayleigh SAW on ST-X quartz without a ZnO film. However, k_s of a Rayleigh SAW on IDT/ZnO/shorted-plane/quartz requires a thick ZnO film ($H/\lambda \geq 0.7$) to obtain $k_s = 0.1$. In contrast, as shown in this figure, the k_s values of Sezawa SAWs obtained are very small because the Rayleigh SAW velocity on the quartz substrate is low. The values of the phase velocity, the k_s, and the TCF were calculated for IDT/ZnO/quartz substrates (29°45′-rotated Y–35° X or 42°45′-rotated Y–35° X quartz substrates). The TCFs were calculated by substituting the phase velocities [V(0 °C), V(20 °C), V(40 °C)] at 0, 20, and 40 °C into the following equation, for comparison with later measured results:

$$\mathrm{TCF} = [V(40\ °\mathrm{C}) - V(0\ °\mathrm{C})]/[40 \times V(20\ °\mathrm{C})] - \alpha \quad (2)$$

Two types of TCFs were calculated for the cases in which the surface of the ZnO film was electrically open or shorted (velocity: V_f and V_m). The calculated values are shown with the measured values in Figs. 7 and 8.

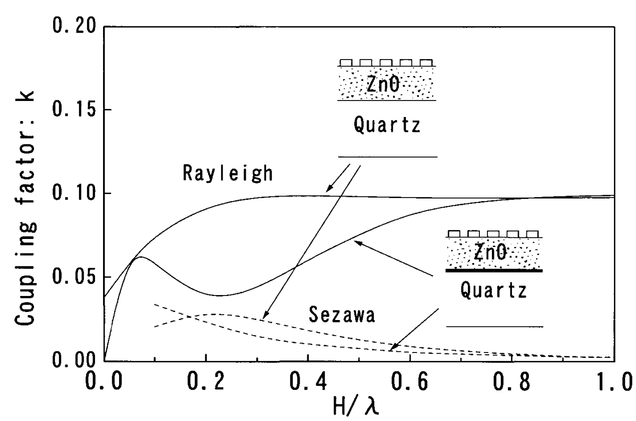

Fig. 3. ZnO thickness dependence of calculated electromechanical coupling factor.

2.3. Measured results

After deposition of a ZnO film to a thickness of 4.5 to 7 μm on the 29°45′-rotated Y and 42°45′-rotated Y quartz substrates using an RF magnetron mode electron cyclotron resonance (RF-Mg-ECR) or a conventional RF magnetron (Con. RF-Mg) sputtering system, aluminum IDTs were formed by a liftoff method on the ZnO film in the direction of 35° X SAW propagation to provide the above-mentioned IDT/ZnO/quartz structure. A SAW filter consists of two normal IDTs with 20 pairs having various wavelengths of 13 to 72 μm. It was found by X-ray diffraction analysis that the ZnO film formed on these quartz was a polycrystalline *c*-axis-oriented film.

2.3.1. Measured results of velocity and coupling factor

The dependence of the velocity and k_s on ZnO film thickness is shown in Figs. 4 and 5. Theoretical values for the ZnO on the 29°45′-rotated Y–35° X and 42°45′-rotated Y–35° X quartz substrates are shown by solid and dashed lines, respectively. Measured values for ZnO/29°45′-rotated Y–35° X and 42°45′-rotated Y–35° X quartz substrates deposited using the RF-Mg-ECR sputtering system are plotted as ○ and ●, respectively, and those for substrates deposited using the Con. RF-Mg sputtering system as × and +, respectively. In these figures, the measurement results are only for Rayleigh SAWs. Values for the Sezawa SAW were not measured. A slight difference was observed in the theoretical velocity and that measured by RF-Mg-ECR for the thin ZnO film deposited at ZnO film thicknesses H/λ = 0.03 to 0.13; however, good agreement was obtained with respect to the other velocities and k_s values. In the range of H/λ = 0.2 to 1.0, a large value of k_s (= 0.1) is obtained which is identical to the theoretical value. The coupling factor values of the 29°45′-rotated Y plate and the 42°45′-rotated Y plate are almost identical, both experimentally and theoretically. The SAW velocity was obtained from the center frequency of the SAW filter and the wavelength. The measured k_s was determined by measuring the radiation conductance of a conductance circle of the above-mentioned normal IDT [14–16].

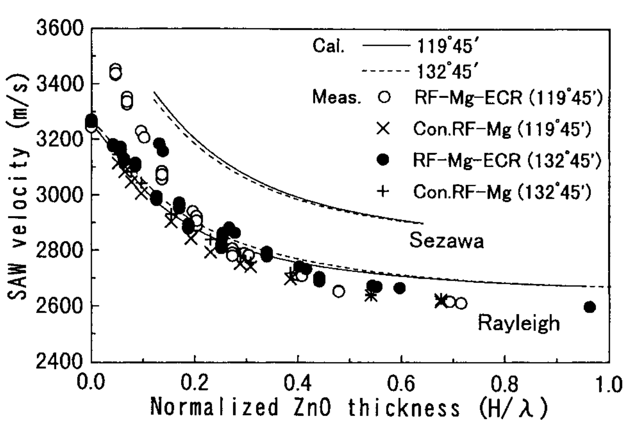

Fig. 4. SAW velocity relative to ZnO thickness on ST-35° X quartz.

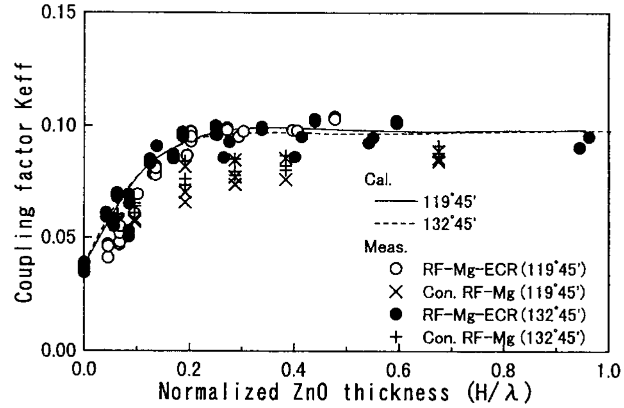

Fig. 5. Electromechanical coupling factor relative to ZnO thickness on ST-35° X quartz.

Figure 6 shows frequency characteristics of SAW filters on 29°45′-rotated Y–35° X quartz substrates with and without the ZnO film. These SAW filters consist of IDTs having λ = 26 μm and H/λ = 0.22. They were measured

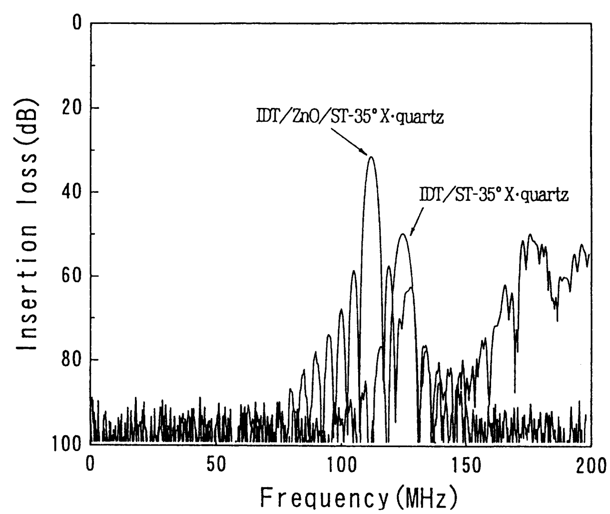

Fig. 6. Frequency characteristics of SAW filters on 29°45′Y–35° X quartz with and without ZnO film.

under the condition of 50 Ω without electrical matching. By depositing the ZnO film on the quartz substrate, the center frequency of the SAW filter was decreased from 125 MHz to 112 MHz and the insertion loss of 18 dB was improved from 50 dB to 32 dB. These results are based on the change of SAW velocity and coupling factor shown in Figs. 4 and 5. It is considered that the difference in insertion losses of SAW filters between ST-X quartz without the ZnO film and ZnO/29° Y-rotated 35° X quartz is about 18 dB, because ST-X and ST-35° X quartz substrates without the ZnO film have almost the same k_s as the Rayleigh SAW.

2.3.2. Measured results of TCF

The center frequencies of the SAW filters were measured at temperatures from –20 to +80 °C. Figures 7 and 8 show TCF for 0 to 40 °C measured and calculated using Eq. (2) for a SAW filter on IDT/ZnO/29°45′-rotated Y–35° X and 42°45′-rotated Y–35° X quartz as a function of the ZnO thickness in the range H/λ = 0 to 0.54. Solid and dashed lines indicate the calculated values of V_f and V_m, respectively; ○, ●, ×, and + show measured results for substrates deposited by the same sputtering systems as in Figs. 4 and 5. It is clear that, as a result of the deposition of ZnO with a negative TCF on quartz having a positive TCF, TCF shifts were measured from a positive TCF to a negative TCF in proportion to the ZnO thickness. Furthermore, a zero value of TCF was realized at ZnO thicknesses H/λ = 0.13 to 0.25, as in these figures. The obtained results agree satisfactorily with those expected by the author. As shown in these figures, zero TCFs can be realized on 29°45′-rotated Y–35° X and 42°45′-rotated Y–35° X quartz substrates at H/λ = 0.3 and 0.22, respectively, in the case of Con.RF-Mg sputtering. On the other hand, in the case of RF-Mg-ECR sputtering, zero TCF on both substrates can be realized at H/λ = 0.13, which is close to the calculated thickness. In both figures, the ZnO film thickness in RF-Mg-ECR sputtering at which zero TCFs are realized is less than that in Con.RF-Mg sputtering. It is considered that the ZnO film fabricated by RF-Mg-ECR sputtering is denser than that fabricated by Con.RF-Mg sputtering.

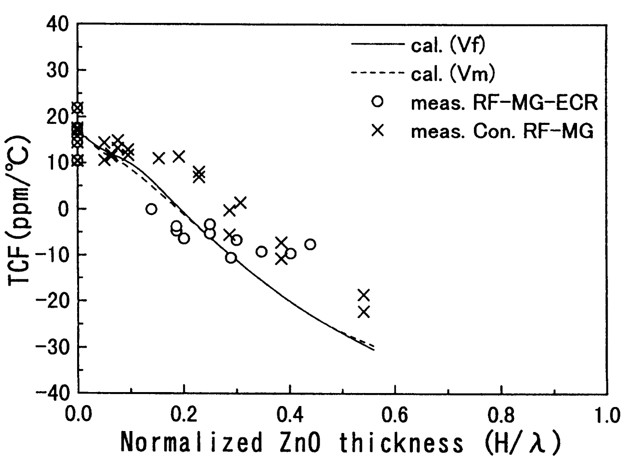

Fig. 7. TCF relative to ZnO thickness on 29°45′Y–35° X quartz.

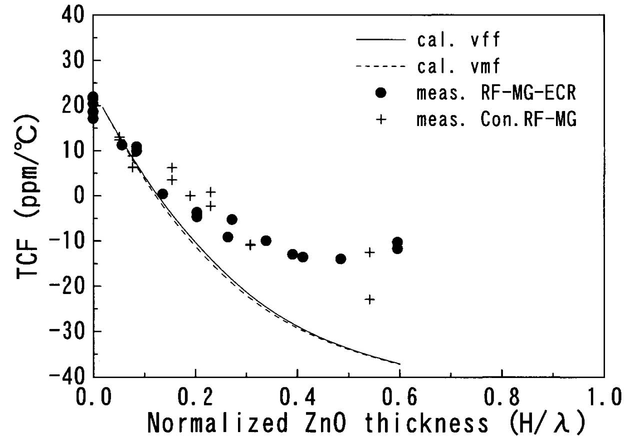

Fig. 8. TCF relative to ZnO thickness on 42°45′Y–35° X quartz.

The TCF of a SAW device on a quartz substrate without ZnO film is affected by the thickness of the aluminum IDT. TCFs of SAW filters having five normalized Al-IDT thicknesses H_{Al}/λ (= 0.002, 0.003, 0.006, 0.009, 0.011) were measured. It is considered that the variation of the TCF of SAW filters consisting of quartz substrates without ZnO film (H_{ZnO}/λ = 0) is due to the different normalized Al-IDT thicknesses.

Table 1 shows the Rayleigh SAW properties of various SAW substrates having a good TCF, such as ST-cut X-propagation quartz, $Li_2B_4O_7$, and $La_3Ga_5SiO_{14}$ [1, 11, 17]. In this table, the measured frequency shift is (total

Table 1. SAW properties of substrates with good TCF

Substrate	Velocity (m/s)	k^2_s	PFA	Frequency shift (ppm/℃)
ST-X quartz [11]	3158	0.0014	0°	0.9
$La_3Ga_5SiO_{14}$ [1] (12°,152.7°,37°)	2835	0.0046	0°	1.55
$Li_2B_4O_7$ (110°,90°,90°)	3480	0.01	0°	6.8
IDT/ZnO/quartz (ST-cut 35°X)	2900	0.01	0°	1.1

frequency shift)/(measured temperature range) (ppm/°C). The measured results for $La_3Ga_5SiO_{14}$ are the latest ones since our most recent paper [1]. It is clarified that the IDT/ZnO/ST-cut 35° X quartz realizes an excellent TCF, a large coupling factor (k_s^2 = 0.01), and a low SAW velocity. This substrate is suitable for Rayleigh SAW devices.

2.3.3. SAW filter for W-CDMA first IF stage

Figure 9 shows the frequency characteristics of the first IF filter for a wide-band CDMA consisting of ZnO/42°45′-rotated Y–35° X quartz. This filter consists of a transversal filter with a normal IDT and an apodized IDT, and has an insertion loss of 14.7 dB and a 3-dB bandwidth of 6 MHz. Since this filter has lower velocity, its size, 5 × 7 mm, is 10% smaller than that of a filter consisting of a Rayleigh SAW of ST-X quartz. It would be possible to realize an even smaller size and an even lower loss by applying a suitable design.

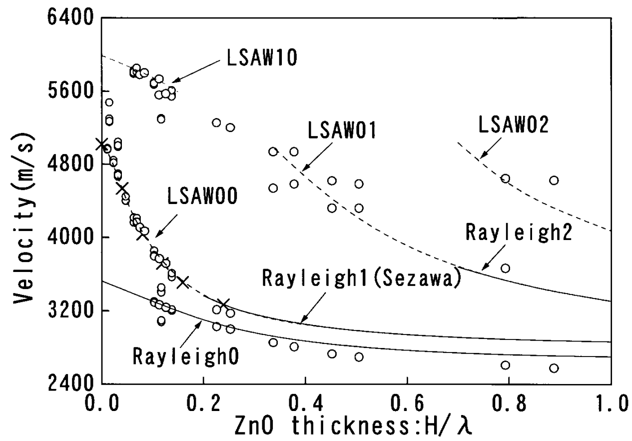

Fig. 10. SAW velocities relative to ZnO thickness on 42°45′Y–90° X quartz.

3. LSAW and Its Higher Modes on ZnO Film on ST-90° X Quartz

It is considered that fundamental LSAW or its higher modes having an excellent TCF and a higher velocity are generated by combining ZnO film with a negative TCF and a quartz substrate with a positive TCF and a high LSAW velocity, as mentioned above. ST-cut X and 90° X-propagation quartz substrates have high LSAW velocities, as shown in Fig. 2. LSAW of ST-90° X quartz has a positive TCF while that of ST-X quartz has a negative TCF, as reported in Ref. 10. It is more advantageous to use the combination of ZnO film and an ST-90° X quartz substrate with positive TCF. Figures 10 and 11 show the calculated and measured SAW phase velocities and k_s values for ZnO/42°45′-rotated Y–90° X quartz (Euler angles: 0°, 132°45′, 90°). Campbell's method was applied to the analysis of LSAW. The ZnO films were deposited on the quartz substrates after IDTs of 20 pairs consisting of various wavelengths (7.4 to 7.8 μm) were formed on them. The input and output IDTs consist of single and split electrodes, respectively. Transversal SAW filters with the ZnO/IDT/quartz structure were used for the experiment. The IDT position and the SAW propagation direction of these filters are different from those of the IDT/ZnO/ST-

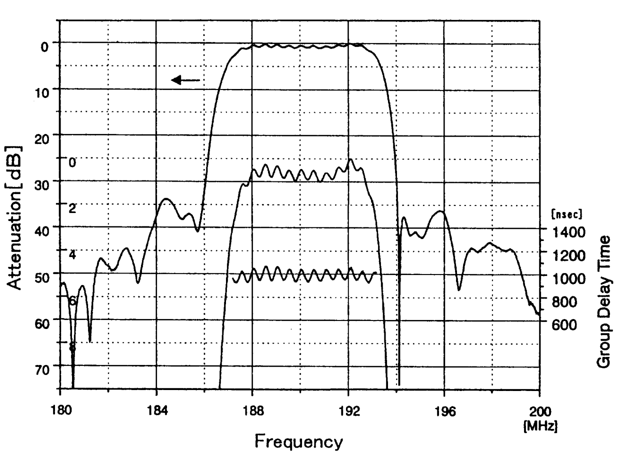

Fig. 9. Frequency characteristics of SAW filters for W-CDMA on IDT/ZnO/42°45′Y–35° X quartz.

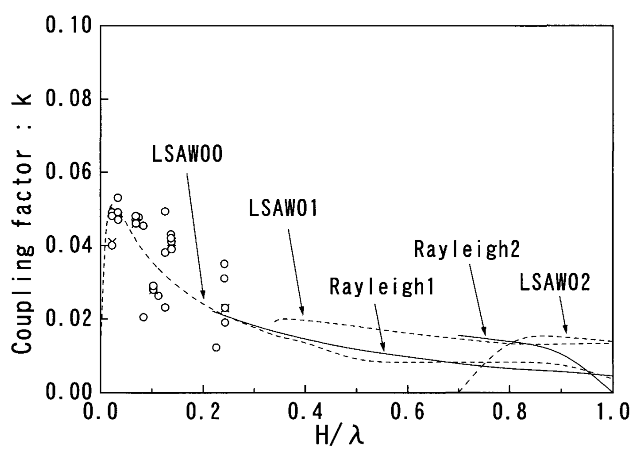

Fig. 11. SAW coupling factors relative to ZnO thickness on 42°45′Y–90° X quartz.

35° X quartz structure for Rayleigh SAW. The ZnO film was deposited using the RF-Mg-ECR sputtering system.

In Fig. 10, the solid lines show a Rayleigh 0th wave and its higher modes [1st (Sezawa wave), 2nd, and 3rd], and the dashed lines show the fundamental mode of LSAW and its higher modes. The LSAWs shift from left to right in the figure, and are sequentially indicated as LSAW00, LSAW01, and LSAW02 as the ZnO film becomes thicker. An LSAW with higher velocity than that of LSAW00 was indicated to be LSAW10 at the same film thickness as LSAW00. The fundamental LSAW and its higher modes are generated as the ZnO film becomes thicker. In addition, the higher modes of the Rayleigh wave having almost the same velocity as the LSAWs are also generated as the ZnO film becomes thicker. That is, LSAW00 is excited at a ZnO thickness $H/\lambda < 0.1$, and the Rayleigh 1st SAW, which has almost the same velocity as LSAW00, is generated at $H/\lambda \geq 0.1$. Moreover, a Rayleigh 2nd wave having almost the same velocity as LSAW01 is generated at $H/\lambda \geq 0.63$, and a Rayleigh 3rd SAW wave having almost the same velocity as LSAW02 is generated at $H/\lambda \geq 0.71$. The measured velocities and k_s values are close to the calculated values. The fundamental LSAW and its higher modes have high velocities. LSAW00 has a high velocity of 4400 m/s and a k_s of 0.052 ($k_s^2 = 0.003$), which are larger than those of the Rayleigh SAW on ST-X quartz at $H/\lambda = 0.05$.

The TCFs and the propagation losses (decay coefficients) are shown in Figs. 12 and 13. LSAW00, LSAW01, and LSAW02 have TCF ≃ zero, but the Rayleigh 0th and its higher modes do not have TCF ≃ zero. Because the propagation loss of LSAW10 is large, it is not a practical SAW substrate for SAW device application. On the other hand, because the propagation losses of LSAW00, LSAW01, and LSAW02 are almost zero, they are practical.

Figure 14 shows an example of the frequency characteristic of a transversal SAW filter with an IDT of $\lambda = 26$ μm and a ZnO film thickness of $H/\lambda = 0.069$. Two kinds of SAWs are generated: the lower SAW is LSAW00 and the higher SAW is LSAW10. Their velocities are 4110 and 5850 m/s, respectively: the latter shows a higher velocity than the Sezawa wave (5200 m/s) of ZnO/sapphire. Figure 15 shows the frequency characteristic of a SAW filter with an IDT of $\lambda = 17.4$ μm and a ZnO film thickness of $H/\lambda = 0.378$: the lower SAW is the Rayleigh 0th wave and the higher one is LSAW01.

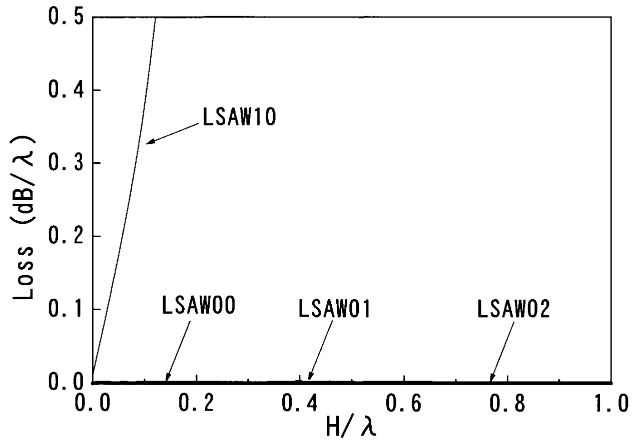

Fig. 13. LSAW decay constants relative to ZnO thickness on 42°45′Y–90° X quartz.

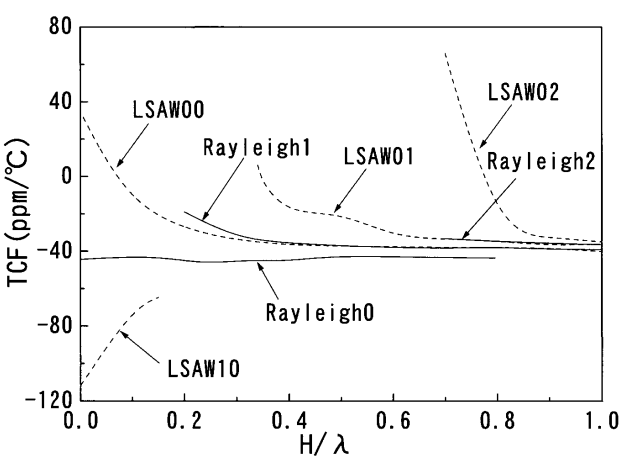

Fig. 12. TCFs relative to ZnO thickness on 42°45′Y–90° X quartz.

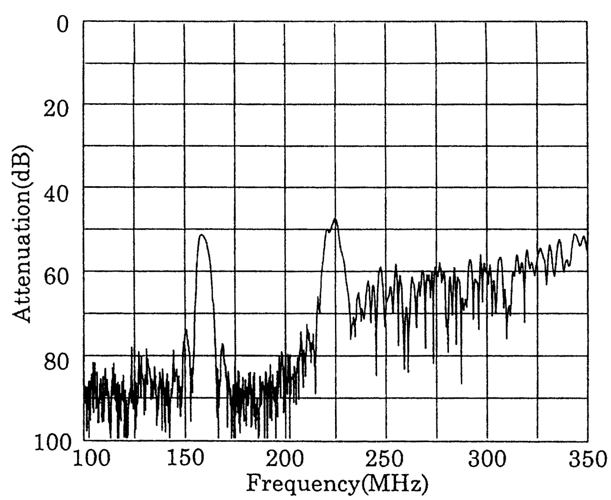

Fig. 14. Frequency characteristic of SAW filter having $\lambda = 26$ μm of IDT at normalized ZnO thickness $H_{ZnO}/\lambda = 0.069$.

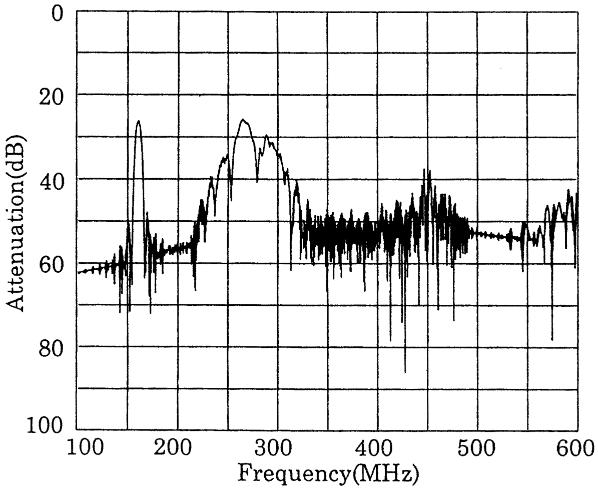

Fig. 15. Frequency characteristic of SAW filter having $\lambda = 17.4$ μm of IDT at normalized ZnO thickness $H_{ZnO}/\lambda = 0.378$.

Therefore, the fundamental-mode LSAW00 and higher mode LSAW01 showed TCF = 0, high velocities of 4400 to 4300 and 4920 m/s, and k_s of 0.05 to 0.04 and 0.02, respectively, at $H/\lambda = 0.05$ to 0.06 and 0.35, respectively. It was clarified that a substrate having good TCF and high velocity was obtained by combining the ZnO film and the quartz substrate having a high LSAW velocity.

The calculated and measured velocity values of the combined ZnO film and 29°45′–90° X and 35°15′–90° X quartz substrates showed results similar to those in Fig. 10, though they are not indicated here for lack of space [7–9]. It is not necessary to use an ST-90 °X quartz substrate in order to obtain a high LSAW velocity. It is considered that a higher LSAW velocity can be obtained by combining a ZnO film and a specific cut and propagation angle quartz substrate with a high LSAW velocity. The LSAW00 for the combined ZnO film and GT-cut X-propagation quartz (Euler angles: 0°, 141°, 0°) has a good TCF (≃ 0) and a high velocity (4500 m/s) at a ZnO thickness of $H/\lambda = 0.05$ [7–9]. It may be possible to obtain a substrate having a good TCF, a large k_s, and a high velocity by combining other cut-angle quartz substrates and ZnO films, but this involves further challenges.

4. Conclusion

The quartz substrate for Rayleigh wave devices has an excellent TCF and a low velocity, but it does not have a large k_s. The SAW substrate for SAW resonators, resonator-type filters, and ladder-type SAW filters is required to have an excellent TCF and a suitable k_s to achieve the desired bandwidth. The substrate for high-frequency SAW devices is required to have a suitable TCF and a high velocity. The author performed a theoretical analysis and experiments to realize the following two types of substrates, and obtained good results.

(1) The author realized a Rayleigh SAW substrate having an excellent TCF ≃ 0 ppm/°C, an appropriate coupling factor ($k_s = 0.1$; $k_s^2 = 0.01$), zero power flow angle, and small SAW velocity, on an IDT/ZnO/quartz structure at a ZnO thickness $H/\lambda \simeq 0.13$, for the first time by combining a quartz substrate having a positive TCF (that is, 29°45′-rotated Y and 42°45′-rotated. Y–35° X propagating substrate) and a ZnO film having a negative TCF. The value of this k_s is 7 times that of the ST-X quartz, and 2.4 times that of a langasite crystal. The insertion loss of the 125-MHz transversal SAW filter has been improved by 18 dB by depositing a ZnO film on a quartz substrate. The filter for W-CDMA consisting of this structure also showed a good frequency characteristic. It is expected that these substrates will be used widely in devices which require an excellent TCF, an appropriate electromechanical coupling factor (= 0.1), and miniaturization of the SAW device size.

(2) It was confirmed experimentally and theoretically that not only higher modes of the Rayleigh SAW but also the fundamental LSAW and its higher modes having a good TCF and high velocity were generated by combining a ZnO film with a negative TCF and ST-90° X quartz with a positive TCF and high velocity. It is expected that a fundamental LSAW and its higher modes having a good TCF, a large k_s, and a high velocity would be obtained by combining the ZnO film and the quartz with other cut and propagation angles.

It is considered that substrates with various features as described above will be realized in the future by combining ZnO films with specific substrates.

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