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Analysis of Longitudinal Leaky SAW on $LiNbO_3$ Thin Plate/Amorphous Layer/Quartz Structure

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***Abstract*—To obtain bonded structure with a low residual stress and a low attenuation for longitudinal leaky surface acoustic waves (LLSAWs), the propagation and resonance properties of an LLSAW on an amorphous layer inserted between $LiNbO_3$ (LN) thin plate and an X-cut quartz substrate were theoretically analyzed. The attenuation of LLSAW on the metallized surface of an X-cut 36°Y-propagating LN (X36°Y-LN)/Al_2O_3/X35°Y-quartz structure was calculated to be 0.0001 dB/λ at the normalized LN thin-plate thickness h/λ=0.072 (λ: wavelength) and was lower than that on an X36°Y-LN/X35°Y-quartz structure. Using a finite element method (FEM) system for analysis, for the X36°Y-LN/Al_2O_3/X35°Y-quartz model, we found that the Q factor was improved to 82,000 from 15,000 for the X36°Y-LN/X35°Y-Q model. It is considered that the attenuation was reduced by the suppression of the leakage of the shear vertical component when the Al_2O_3 layer was inserted. For the same structure, but in which the mechanical loss Q_m of 1,000 for LN was assumed, the Q factor was determined to be 2,500 and 1,900 with and without an inserted amorphous Al_2O_3 layer, respectively.**

Keywords—longitudinal leaky SAW; quartz; bonded structure

I. INTRODUCTION

To develop next-generation mobile communication systems, high-performance surface acoustic wave (SAW) devices with a high frequency, a large electromechanical coupling factor (K^2), and a large Q factor are required. The conventional SAW propagation modes used for SAW filters include Rayleigh-type SAWs (R-SAW) and leaky SAWs (LSAWs). In recent years, longitudinal LSAWs (LLSAWs) have been attracting increased interest because of their phase velocity being higher than that of conventional SAW propagation modes. However, they have inherent attenuation, which is disadvantageous for obtaining a large Q factor because they lose energy by continuously radiating two types of bulk wave, namely, shear horizontal (SH) and shear vertical (SV) waves, into the substrate.

Therefore, it is difficult to achieve the above requirements only with a single $LiTaO_3$ (LT) or $LiNbO_3$ (LN) substrate. For these reasons, LLSAWs have been studied by focusing on the material and on substrate structures with various combinations of materials.

For example, an LLSAW resonator with a high frequency and a large impedance ratio using a $LiNbO_3$ thin plate and a multilayered acoustic reflector comprising a SiO_2/Pt layer has been realized [1]. In addition, employing a wurtzite ScAlN with a high phase velocity and a high piezoelectricity, a layered structure consisting of (0°, θ, ψ) $Sc_xAl_{1-x}N$ film/X-cut $LiNbO_3$ substrate has been reported [2]. On the other hand, our research group reported a theoretical and experimental investigation of the propagation properties of LLSAWs on an LT or LN thin plate bonded to a quartz substrate [3,4]. Furthermore, it was shown that the attenuation during propagation, which is important for obtaining a high Q, is markedly reduced when X-cut quartz is used as the support substrate [5].

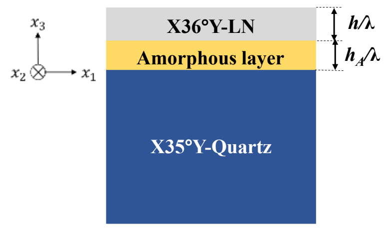

Fig. 1. Analysis model of X36°Y-LN/amorphous layer/X35°Y-Q structure.

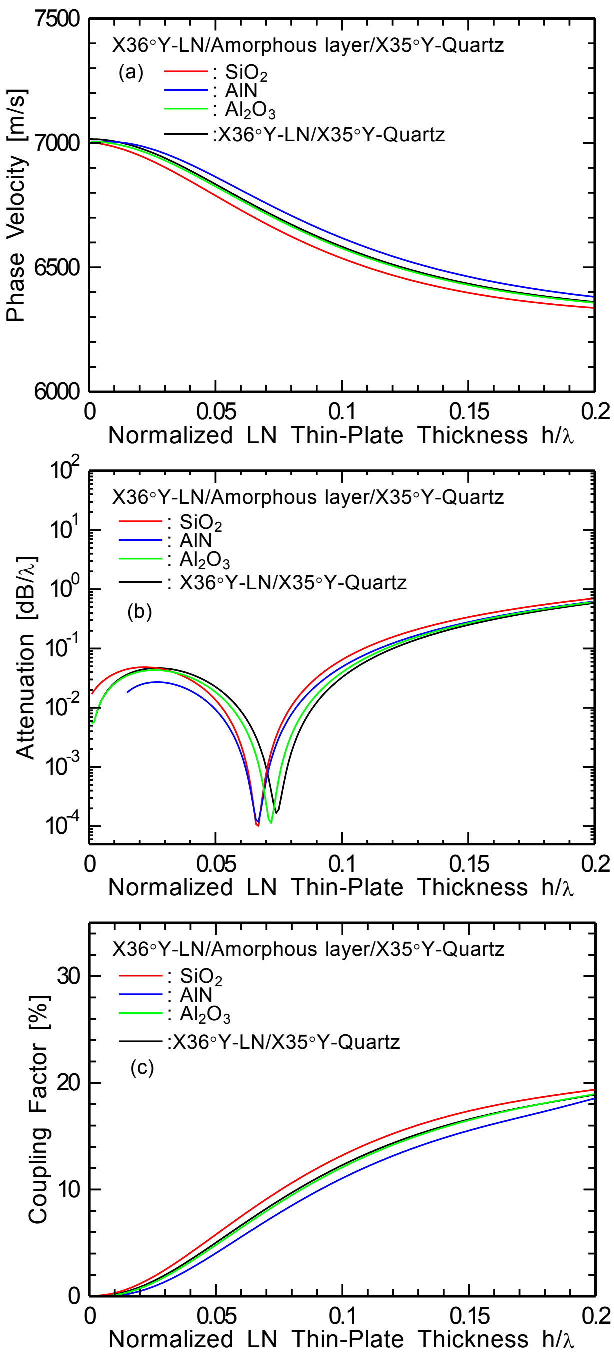

Fig. 2. (a) Phase velocity, (b) attenuation, and (c) K^2 as a function of normalized LN thin-plate thickness for LLSAW.

However, the measured Q factors and temperature coefficients of the frequency were different from the theoretical values owing to the nonuniformity of the bonding interface. To improve these values, the residual stress was decreased and the strength of the bond between the LN thin plate and the quartz substrate was greatly increased by using amorphous SiO_2 and Al_2O_3 thin films of 50 nm thickness formed by ion beam sputtering as an intermediate layer [6].

In this study, the propagation and resonance properties of an LLSAW on an amorphous layer between an LN thin plate and a quartz substrate were investigated.

II. Analytical Solution

The analysis of an LLSAW with attenuation was based on the method of Yamanouchi and Shibayama [7]. The phase velocity and attenuation of an LLSAW on a layered structure for an electrically free and metallized surface were calculated by Farnell and Adler's SAW propagation analysis [8], where the material constants of the LT and quartz reported by Kushibiki and co-workers were used [9,10].

The analysis model was shown in Fig. 1. First, the phase velocity, attenuation, and K^2 were calculated for metallized surfaces in the case of an LLSAW on an amorphous layer inserted between an X-cut 36° Y-propagating LN (X36°Y-LN) thin plate and an X-cut 35° Y-propagating quartz (X35°Y-Q) substrate. Figure 2 shows (a) the phase velocity, (b) attenuation, and (c) K^2 of the LLSAW as a function of the normalized LN thin-plate thickness (h/λ). SiO_2, AlN, and Al_2O_3 were selected as the materials of the amorphous layer. The above-mentioned film thickness h_A was set to 0.01λ. K^2 was determined from the relation $K^2=2(v_f-v_m)/v_f$ where v_f and v_m are the phase velocities on the free and metallized surfaces, respectively. The results for the case without the amorphous layer are also shown in these figures.

As shown in Fig. 2(a), when SiO_2 and AlN were inserted, the phase velocity decreased and increased, respectively. Al_2O_3 was found to have a negligible effect on the phase velocity. This is considered to be due to the phase velocity of the amorphous layer. In addition, as the LN film thickness increased, the phase velocity approached that of single LN. As shown in Fig. 2(b), the minimum attenuation on the metallized surface of the X36°Y-LN/amorphous layer/X35°Y-Q structure shifted to a smaller LN thin-plate thickness. The Al_2O_3 layer was found to have a negligible variation in minimum attenuation. The minimum attenuation was 0.0001 dB/λ at h/λ of 0.072. This value is lower than that in the case where no amorphous layer is inserted; therefore, the Q factor is expected to be large. Also, as shown in Fig. 2(c), the K^2 of the LLSAW increased with h/λ. At h/λ with the minimum attenuation, the K^2 of the LLSAW was determined to be 9.1%, 7.0%, and 8.0% for SiO_2, AlN, and Al_2O_3, respectively. The results indicate that inserting an amorphous layer increases the bonding strength while maintaining a high frequency and a large K^2. In addition, the improvement of the Q factor can be expected.

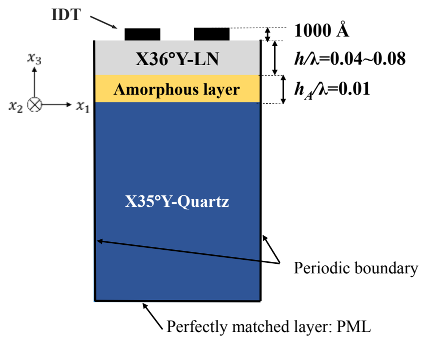

Fig. 3. Outline of the model constructed for FEM analysis.

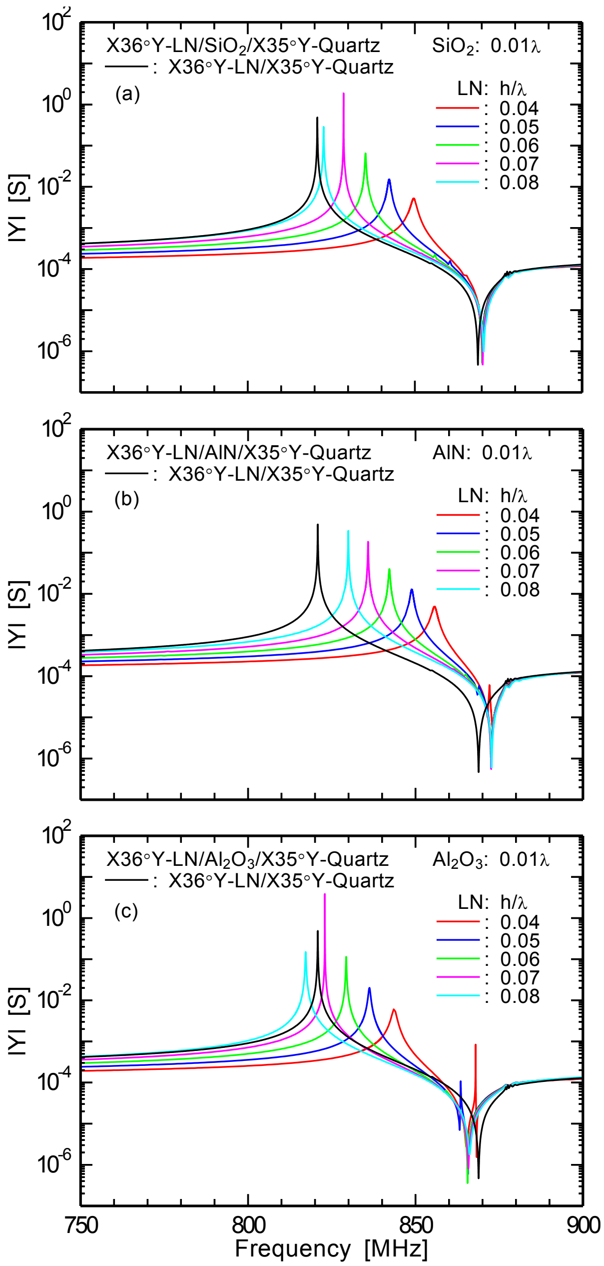

Fig. 4. Simulated resonance properties of LLSAW for (a) SiO_2, (b) AlN, and (c) Al_2O_3.

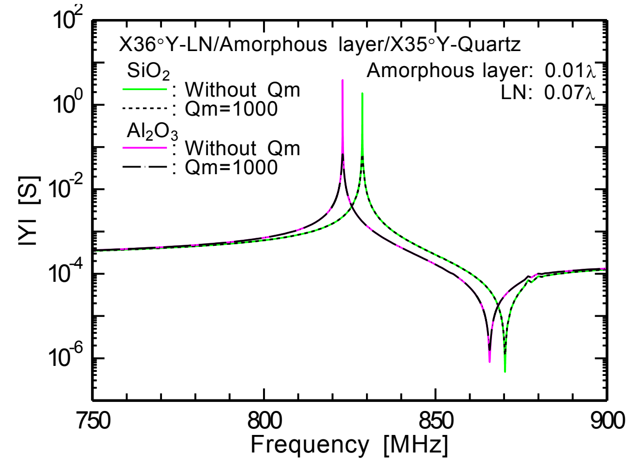

Fig. 5. Simulated resonance properties of LLSAW including Q_m with inserted SiO_2 or Al_2O_3.

III. Finite Element Method Analysis

Using a finite element method (FEM) system, the ideal resonance properties of an LLSAW on X36°Y-LN/amorphous layer/X35°Y-Q was simulated. Figure 3 shows an outline of the model used for FEM analysis. In the analysis, a model with one period of an interdigital transducer (IDT) with a period λ of 8.0 µm and an aperture width (W) of 25λ (1,000-Å-thick Al) and a substrate thickness of 10λ was constructed. The side of the model was set to have a periodic boundary, and a perfectly matched layer (PML) was assumed for the bottom of the substrate to prevent the reflection of waves. The LN thin-plate thickness h and amorphous film thickness were set to 0.04λ–0.08λ and 0.01λ, respectively. The same structure with inserted SiO_2 or Al_2O_3, but in which the mechanical loss Q_m of LN was taken into consideration, was also simulated.

Figure 4 shows the simulation results for these structures with (a) SiO_2, (b) AlN, and (c) Al_2O_3 for a sinusoidal AC voltage of ±1 V applied to the IDT. The Q factor when h/λ was 0.07 (0.08 for (b)) was found to be 64,000, 10,000, and 82,000, respectively. By inserting an Al_2O_3 layer, the Q factor was significantly improved compared with that of 15,000 for X36°Y-LN/X35°Y-Q with h/λ=0.08. The Q factor obtained when AlN was inserted did not exceed that obtained without an amorphous layer. It is considered that had no concentration effect occurred on the surface because the single AlN layer had a higher phase velocity than the quartz substrate. Figure 5 shows the simulation results including the Q_m of LN for the structures with SiO_2 or Al_2O_3. When Q_m of 1,000 was assumed, the Q factors were 2,400, 2,500, and 1,900 with inserted SiO_2 and Al_2O_3 and without an amorphous layer, respectively.

Furthermore, to discuss the low attenuation achieved upon inserting the Al_2O_3 layer in X36°Y-LN/X35°Y-Q, we examined the particle displacements u_1, u_2, and u_3, which are the main displacement and the SH and SV components of the LLSAW at the resonance frequency (f_r), respectively. Figure 6 shows the simulated particle displacements u_1, u_2, and u_3 for the LLSAW on (a) X36°Y-LN/X35°Y-Q and (b) X36°Y-LN/Al_2O_3/X35°Y-Q. As shown in Fig. 6(a), u_1 and u_2 were

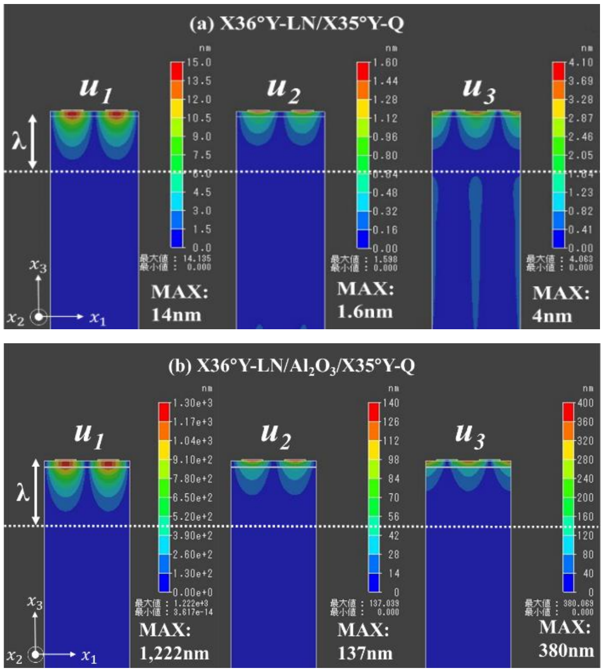

Fig. 6. Simulated particle displacements for LLSAW on (a) X36°Y-LN/X35°Y-Q and (b) X36°Y-LN/Al_2O_3/X35°Y-Q.

concentrated on the surface. Also, as shown in Fig. 6(b), u_1, u_2, and u_3 were concentrated in the vicinity of the surface.

Therefore, it is considered that the attenuation was reduced by the suppression of the leakage of the SV component when the Al_2O_3 layer was inserted. In addition, the increase in the amplitude of the main displacement is also a cause of the large Q factor.

IV. Conclusions

In this study, to obtain a bonded structure with a low residual stress and a low attenuation for LLSAWs, the propagation and resonance properties of an LLSAW on an X36°Y-LN/amorphous layer/X35°Y-Q structure were investigated theoretically. The attenuation of LLSAW on the metallized surface with an inserted Al_2O_3 structure was calculated to be 0.0001 dB/λ at h/λ=0.072 and was lower than that on an X36°Y-LN/X35°Y-Q structure. In addition, Al_2O_3 was found to have a negligible effect on the K^2 of the LLSAW on the structure.

Using an FEM system, the inserted Al_2O_3 layer with the X36°Y-LN/X35°Y-Q structure was found to be effective for improving the Q factor of the LLSAW through the concentration of the particle displacements on the surface. The Q factor was improved to 82,000 from 15,000 for the X36°Y-LN/X35°Y-Q model. When the mechanical loss Q_m of 1,000 for LN was assumed, the Q factor was determined to be 2,500 and 1,900 with and without an inserted amorphous Al_2O_3 layer, respectively.

In the future, the X36°Y-LN/Al_2O_3/X35°Y-Q structure will be investigated experimentally.

Acknowledgments

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