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Proceedings of Symposium on Ultrasonic Electronics, Vol. 32 (2011) pp. 227-228
8-10 November, 2011

Loss Reduction of Longitudinal-Type Leaky SAW by Reverse Proton Exchange
逆プロトン交換による縦型漏洩弾性表面波の低損失化

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1. Introduction

The longitudinal-type leaky surface acoustic wave (LLSAW) is one of the SAW modes that is advantages for application to high-frequency SAW devices because of its high phase velocity close to that of a longitudinal bulk wave.[1] However, the LLSAW has huge inherent attenuation because it loses energy through the continuous radiation of shear horizontal and shear vertical bulk waves into the substrate.

In previous works, to reduce the attenuation of a leaky SAW (LSAW), we proposed a layered structure of air, a bulk $LiNbO_3$ (LN) layer, and an elastically softened LN substrate and calculated the attenuation. It was found that, for a certain range of the rotation angle of the rotated Y-X LN, attenuation can be reduced by controlling the elastic constant of the softened LN.[2,3] To realize such a layered structure, a reverse proton exchange (RPE) process[4] was applied to 41°Y-X LN and 10°Y-X LN, and the measured propagation losses of the LSAW were decreased by carrying out RPE for a propagation path under a certain electrical condition.[2,3] Furthermore, when the layered structure was applied to X-36°Y LN with a large electromechanical coupling factor K^2 for the LLSAW,[5] zero attenuation for the metallized surface was obtained theoretically at the bulk layer depth of 0.2-0.4 λ (λ: wavelength).[6]

In this study, the above layered structure was fabricated on X-36°Y LN by the RPE process and the propagation and resonance properties of the LLSAW were evaluated.

2. Sample Fabrication

First, an initial PE layer with a depth of 1.7 μm was formed by immersing a 3-inch X-cut LN wafer in a solution of benzoic acid (Li 1.0 mol%) at 250°C for 5.0 h. Next, an RPE layer with a depth of 1.1 μm was formed by immersing the PE wafer in an equimolar mixture of $LiNO_3$-$NaNO_3$-KNO_3 at 300°C for 9.0 h, during which the PE layer was buried in the substrate. The RPE layer was 0.3 λ and was designed in accordance with the results of a theoretical investigation.[6] Finally, input and output interdigital transducers (IDTs) with a period λ of 3.6 μm and 10 split-finger pairs were fabricated on the wafer using an Al film with a thickness of 0.02 λ.

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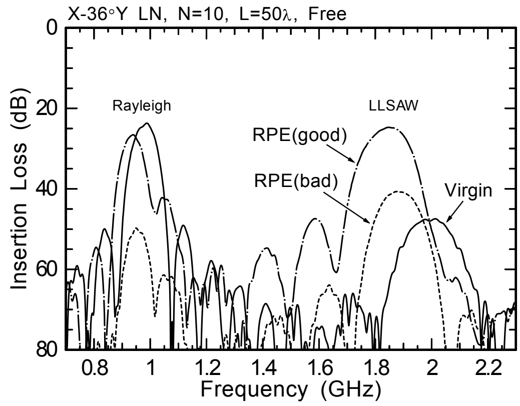

Fig. 1 Frequency responses on X-36°Y LN.

An RPE wafer and a virgin wafer with propagation path lengths of L=5 λ, 10 λ, 25 λ, and 50 λ were fabricated for a free surface, metallized surface, and shorted grating. Resonator electrodes consisting of the IDT with λ=3.6 μm and reflectors with the shorted grating were also fabricated.

3. Propagation Properties

The frequency response between the input and output IDTs was measured by a network analyzer. In general, a PE layer does not exhibit piezoelectricity. It was observed that there was a region on the RPE wafer in which the piezoelectricity was recovered by the RPE process, namely, a “good region,” and a region where the recovery was insufficient, namely a “bad region”. Almost all of the area on the wafer corresponded to the bad region.

The value of K^2 was determined from the measured admittance characteristic of the IDT. For a Rayleigh wave, K^2 for the bad region was 1/40 for that of the virgin wafer. On the other hand, K^2 for the good region was recovered to approximately 80% of that for the virgin wafer. For the LLSAW, K^2 for the virgin wafer was measured to be 1.0%, which was one order of magnitude smaller than the theoretical value (12.9%[4]). Since K^2 of 4.7-6.2% was obtained on the good region, in which the propagation loss was less than that for the virgin wafer as discussed later, a smaller K^2 was observed on the virgin wafer owing its large propagation loss.

Figure 1 shows the measured frequency responses (L=50 λ, free surface) of the good and bad regions on the RPE wafer and the response on the virgin wafer. The minimum insertion loss of the good

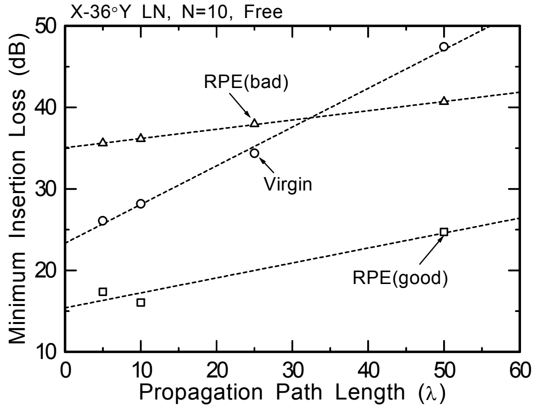

Fig. 2 Minimum insertion loss vs propagation path length on X-36˚Y LN.

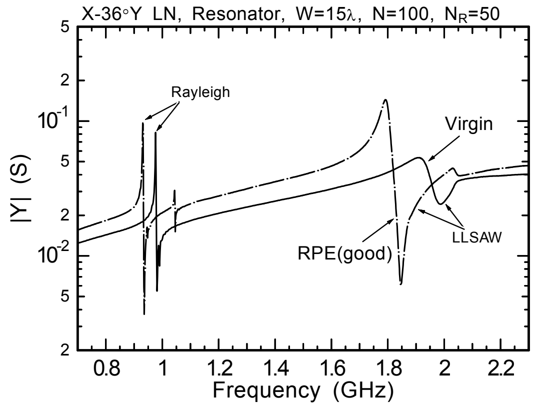

Fig. 3 Admittance properties on X-36˚Y LN.

region on the RPE wafer was decreased to 24.7 dB, approximately 23 dB less than that of the virgin wafer (47.5 dB), and was close to that of the Rayleigh wave on the virgin wafer (23.7 dB). In the bad region, the minimum insertion loss was also less than that of the virgin wafer in spite of the decrease in the piezoelectricity. The LLSAW phase velocities of the virgin wafer and the good region on the RPE wafer were determined to be 7,190 and 6,650 m/s, respectively, from the center frequency. The 7.5% lower value in the good region is considered to be due to the buried PE layer having an elastically softened property.

Figure 2 shows the minimum insertion loss as a function of the propagation path length *L* for the free surface of the two wafers. The propagation loss *PL* was estimated from the slope in Fig. 2 obtained by the least-squares method. *PL* for the free surface was decreased from 0.48 dB/λ of the virgin wafer to 0.18 dB/λ of the good region on the RPE wafer. Even in the bad region, the values of *PL* for the free surface, the metallized surface, and the shorted grating on the RPE wafer were decreased to 1/5-1/4 of that of the virgin wafer.

4. Resonance Properties

Figure 3 shows the measured amplitude of the admittance for the IDT resonator with an aperture of 15 λ, 100 IDT pairs, and 50 refractors. It can be seen that a marked improvement of the resonance properties for the LLSAW was realized in the good region on the RPE wafer. The resonance properties of the Rayleigh wave in the good region were almost the same as those of the virgin wafer because the piezoelectricity was sufficiently recovered by the RPE process.

Details of the improvement to the LLSAW are as follows. The admittance ratio was increased from 6.9 dB to 27.7 dB. The minimum phase reached -55.3˚ with inductivity compared with 34.6˚ for the virgin wafer. The antiresonance quality factor Q was increased fourfold from 34 to 132. On the other hand, the bandwidth ratio $(f_a\text{-}f_r)/f_a$ (f_a: antiresonance frequency, f_r: resonance frequency) was slightly decreased from 3.9% to 3.0%.

The difference between the good and bad regions, which both appeared on the RPE wafer, is considered to be caused by a slight difference in the temperature or Li^+ concentration in the RPE process. It is necessary to identify the cause of the difference and to establish fabrication conditions so that the good region can be formed on the entire wafer surface.

5. Conclusions

A layered structure for the loss reduction of an LLSAW was fabricated on X-36˚Y LN by the RPE process, and the propagation and resonance properties of the LLSAW were evaluated. A good region existed on the RPE wafer, in which the value of K^2 for the Rayleigh wave was recovered to approximately 80% of that of the virgin wafer. In comparison with the virgin wafer, the propagation loss for the free surface of the good region on the RPE wafer was decreased threefold, the insertion loss was decreased drastically, and the resonance properties were improved markedly. In the future, the optimum fabrication conditions to maximize loss reduction will be investigated.

Acknowledgment

The authors would like to thank Dr. K. Hirota and Mr. A. Mori at Nihon Dempa Kogyo Co., Ltd., for their assistance in fabricating the electrodes.

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