High Frequency Lamb Wave Resonator using $LiNbO_3$ Thin Film by CVD

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Abstract— **It has been considered that it is difficult to realize higher frequency devices than 3 GHz by using conventional surface acoustic wave (SAW) substrate. In order to realize a high frequency device, there are some methods such as using a high velocity substrate or shortening a wavelength (λ) of an interdigital transducer (IDT). However, almost of all conventional SAW substrates have a low velocity and it is difficult to shorten the λ of IDT because of too narrow fingers. A Lamb wave has a high velocity and a large coupling factor when a $LiNbO_3$ plate is thiner than 0.2λ. As it is difficult to realize a very thin $LiNbO_3$ crystal plate, author use a thin epitaxial $LiNbO_3$ film deposited by a chemical vapor deposition (CVD). As the result, authors realized a high frequency 4.5 GHz of Lamb wave resonator composed of an electrode/thin epitaxial $LiNbO_3$ film/air gap/base-substrate for the first time. The resonator showed a high velocity of 14,000 m/s, a large impedance ratio of 52 dB, and a wide bandwidth of 7.2 % without spurious response due to SH_0 mode.**

Index Terms— **Lamb wave, 4.5GHz, Resonator, twin epitaxial, $LiNbO_3$ film, CVD**

I. Introduction

Surface acoustic wave (SAW) devices have been used as key devices in various consumer electric equipments such as mobile phones and TV[1]. In recent year, high frequency devices such as RF filters and duplexers in a fourth generation mobile phone are required. There are methods using a high velocity substrate and/or shortening line and space (L & S) of an interdigital transducer (IDT) in order to realize a high frequency device. High frequency devices using high velocity of a bulk wave and a Sezawa wave, and using the narrow L & S on a Rayleigh wave have been reported[2]-[4]. A 9 GHz ladder filter using the bulk wave of AlN thin film and a 10 GHz Sezawa wave transversal filter on a SiO_2 film/ZnO film/diamond film/Si structure had a very narrow bandwidth and a large insertion loss of 22 dB, respectively, because of their small electromechanical coupling factor[2,3]. A 10 GHz Rayleigh SAW transversal filter on an Al-IDT/128°YX-$LiNbO_3$ substrate had too narrow L & S of 0.09 μm[4]. The narrow L&S is not suitable for their reliability of high electric power. So, they are not suitable for above mentioned high frequency devices.

A Lamb wave, which is a kind of plate waves on a thin plate and has a longitudinal and a shear vertical displacements, has a high velocity and a large coupling factor when its substrate plate is very thin, for instant, less than 0.2λ thickness of $LiNbO_3$ plate. On the contrary, a shear horizontal (SH) type plate wave, which is another plate wave having an SH displacement, does not have a high velocity.

The Lamb waves using single crystal plates such as a quartz, a $LiNbO_3$ and a $LiTaO_3$, and piezoelectric films such as a ZnO and a AlN films were reported[5]-[10]. However, all of their operating frequencies were low, for example, lower than 600MHz in the quartz single crystal plate and less than 900 MHz in AlN piezoelectic-thin-film/substrate. And their bandwidths are narrow and their characteristics are not good, for example, the former's 600 MHz filter had a large insertion loss of 22 dB, and the latter's 900 MHz resonator had a small impedance ratio less than 20 dB[5,10]. Moreover, the velocities of their used S_0 mode of Lamb wave were not so high as 5600 m/s and 9000 m/s, respectively, compared with an A_1 mode of the $LiNbO_3$ film described latter[8,9]. It is difficult to realize a very thin crystal plate or a very thin piezoelectric film with a high quality in order to realize a high frequency Lamb wave device. If a very thin $LiNbO_3$ film with a high quality could be deposited instead of the thin crystal plate, it might be possible to realize a high frequency resonator having a large impedance ratio and a wide bandwidth. So, authors have attempted to realize a high frequency Lamb resonator using the $LiNbO_3$ film deposited by a chemical vapor deposition system (CVD). The Lamb wave resonator has been composed of an electrode/$LiNbO_3$ film/air-gap/base-substrate. As the result, the Lamb wave resonator has shown a high resonant frequency of 4.5GHz, which corresponds to a high velocity of 14,000 m/s, a large impedance ratio of 52dB, and a wide bandwidth of 7.2 %. The spurious response due to an SH_0 mode has not been observed because of the effect of the twin epitaxial $LiNbO_3$ film.

II. Theoretical Analysis

Phase velocities and electromechanical coupling factors k^2 of the plate waves propagating in the X-axis direction on a Z-plane $LiNbO_3$ plate (Euler angle (0°, 0°, 0°)) (Z-X) were calculated. A finite element method (FEM) was used in this calculation. When the phase velocities on electrically opened and shorted surfaces are defined as V_f and V_m, respectively, the electromechanical coupling factor k^2 is calculated by $k^2 = 2 \times (V_f - V_m)/V_f$. Figs. 1 and 2 show the calculated phase velocities and the electromechanical coupling factors of the plate waves propagating on the thin Z-X $LiNbO_3$ plate as a function of the plate thickness normalized by a wave

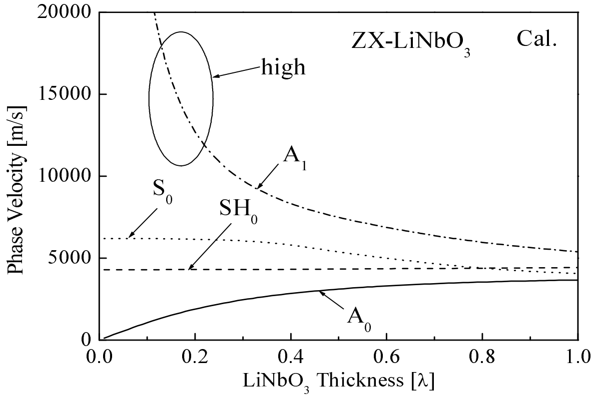


Fig1. Calculated phase velocity of plate waves as function of $LiNbO_3$ thickness.

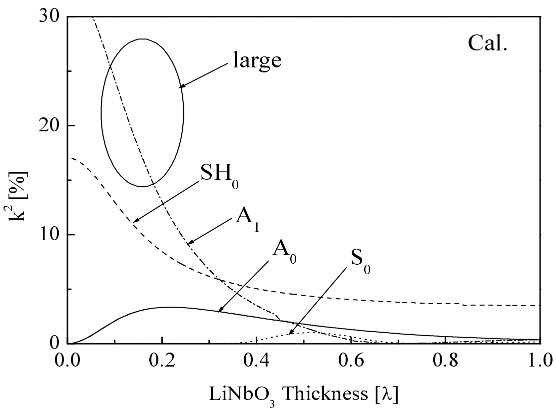


Fig2. Calculated electromechanical coupling factor k^2 of plate waves as function of $LiNbO_3$ thickness.

length (λ) of the acoustic wave, respectively. An A_1 mode of Lamb wave has a high velocity over 12,500 m/s and a large electromechanical coupling factor k^2 over 10 %, when the $LiNbO_3$ plate thickness is thinner than 0.2λ. Although an SH_0 mode has also a large coupling factor, it has low velocity as mentioned above. So, the authors use a Z-plane $LiNbO_3$, which corresponds to c-axis orientated $LiNbO_3$ film, to realize a high frequency device using the A_1 mode of Lamb wave device, because the c-axis orientated thin $LiNbO_3$ film is relatively easy deposited compared with another angle orientated film.

III. Thin $LiNbO_3$ Film and Device Construction

Fig. 3 shows the CVD system. A buffer layer was grown on a base-substrate, before depositing a $LiNbO_3$ film. The $LiNbO_3$ film was deposited on the buffer layer/base-substrate in the reaction room of the CVD shown in Fig. 3, when the Ar gas with Li ions and Nb ions and the O_2 gas were inserted to a reaction room. The thin $LiNbO_3$ film with thickness of about 480 nm was deposited on the buffer layer/base substrate at the substrate temperature of 600 to 700°C using the CVD. The deposition rate was 12 nm/min. After Al-electrodes were

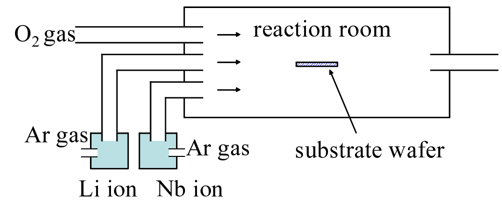


Fig3. CVD system.

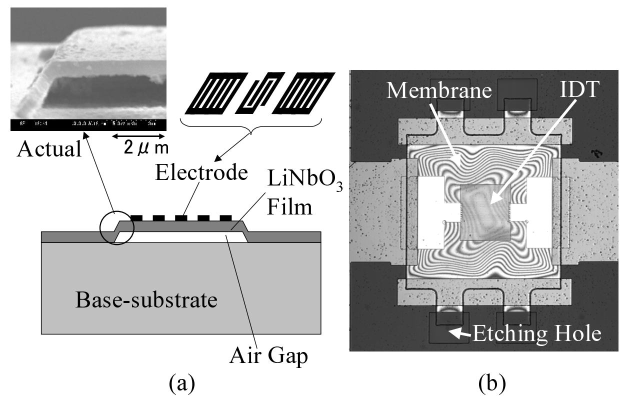


Fig4. Device structure (a) schematic side view and (b) actual top view.

fabricated, the air gap was made by removing the buffer layer.

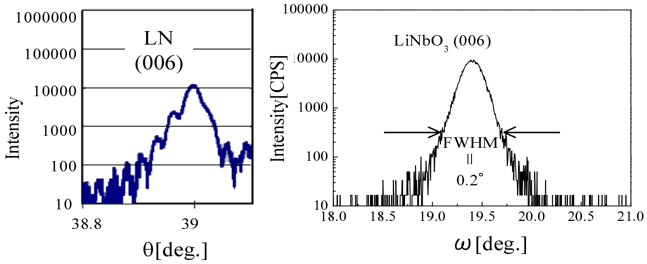
Figs. 4 (a) and (b) show the schematic side view and the actual top view of the fabricated Lamb wave device, respectively. The membrane with size of 200 μm squares was warped, so interference fringes were observed as shown in Fig. 4(b).

Figs. 5 (a) and (b) show measured X-Ray diffraction and rocking curve of the deposited (006) $LiNbO_3$ film, which corresponds to c-orientated. Figs. 5 (a) and (b) show highly c-axis orientated $LiNbO_3$ film because of a narrow full width of half maximum (FWHM) of 0.2°. Figs. 6 (a) and (b) show measured pole figures (ϕscan) of the Z plane $LiNbO_3$ single crystal and the thin $LiNbO_3$ film at (0 1 14) plane, respectively. The former and the latter show 3 and 6 peaks, respectively. The existence of 6 peaks suggests that this thin $LiNbO_3$ film is a twin epitaxial film having two types of single crystals which have 180° rotated relation on c-axis each other as shown in Fig. 6(b).

Fig. 7 shows the polarity of c-axis in the thin $LiNbO_3$ film measured by a scanning nonlinear dielectric microscopy (SNDM)[11]. The black and white regions show the +c and −c domains, respectively. The +c domain occupies 98.5% in Fig. 7. This thin $LiNbO_3$ film has almost plus polarity. It is considered that a mixture of +c and −c domains causes a degradation of the electromechanical coupling factor.

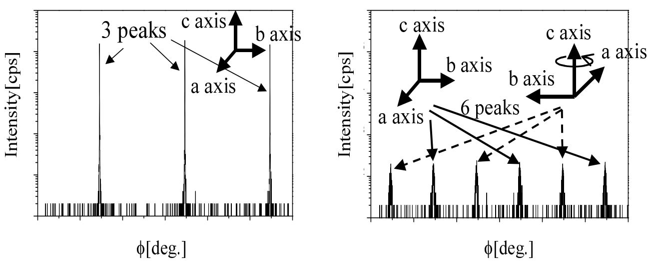
IV. Frequency Characteristics

The Lamb wave one-port resonator is composed of a λ of IDT of 3.2μm, an Al-electrode thickness of 0.03λ, an aperture of the IDT of 15λ, the IDT pairs of 60, each grating reflector



(a) (b)

Fig5. (a) Measured X-Ray diffraction (θ-2θ) and (b) rocking curve of (006) thin $LiNbO_3$ film.



(a) (b)

Fig6. Measured pole figures (ϕscan) of (a) $LiNbO_3$ single crystal and (b) thin $LiNbO_3$ film.

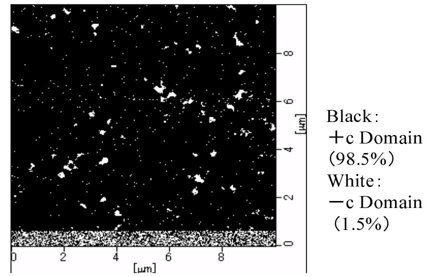


Fig7. Polarity of c-domain in thin $LiNbO_3$ film measured by scanning nonlinear dielectric microscopy.

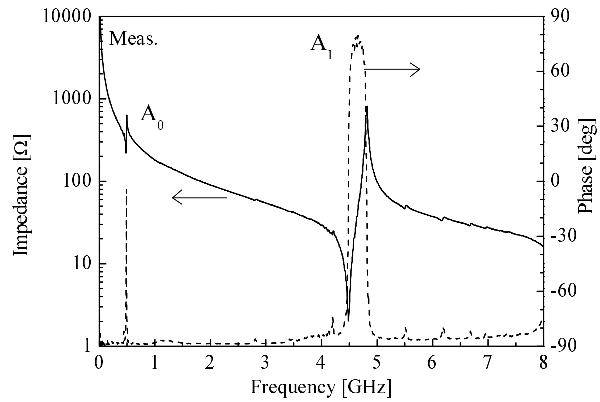


Fig8. Measured impedance and phase characteristics of one-port Lamb wave resonator.

of 20 fingers, and the thin $LiNbO_3$ film thickness of 0.15λ. Fig. 8 shows measured impedance and phase characteristics of the Lamb wave resonator. A response observed at 4 to 5 GHz is an A_1 mode of the Lamb wave, and that observed at 0.5 GHz is an A_0 mode as a result of comparison with the simulation. Though an SH_0 mode on a single crystal plate should be excited at 1 to 1.5 GHz in theoretical result, the SH_0 mode of the resonator composed of the twin epitaxial $LiNbO_3$ film is not observed. Its reason is explained on the following section V. The A_1 mode of Lamb wave has a high resonant frequency of about 4.5 GHz, which corresponds to a high phase velocity of 14,000 m/s, a large impedance ratio of 52dB, and a wide bandwidth of 7.2 %. Where the impedance ratio is $20 \times \log_{10}$(anti-resonant impedance/resonant impedance). The mechanical quality factor Q, at resonant frequency is about 170, and that at anti-resonant frequency is about 90. As a result of fitthing, the electromechanical coupling factor k^2 has been evaluated about 18 %, which is 0.8 times of theoretical one. The reason of a slight deterioration of the coupling factor is considered that the above-mentioned polarity of the thin $LiNbO_3$ film deposited by CVD is not perfectly pure.

V. Twin Epitaxial Effect

A. Simmulation

An influence of the twin epitaxial film of the $LiNbO_3$ on the plate waves is analized. Figs. 9 (a) and (b) show the calculation models. The model (b) is an enlarged one of model (a). Table I shows two type (A) and (B) of the Euler angles for the calculation. The model (b) of thin $LiNbO_3$ plate has 80 devided regions in 1 λ length along the propagating direction, and Euler angle (A) and (B) are applied alternately. When the Euler angle (A) is equal to the Euler angle (B), the $LiNbO_3$ plate is a single crystal. When the Euler angle (A) is different from the Euler angle (B), the $LiNbO_3$ plate is the twin epitaxial film. The $LiNbO_3$ plates' or films' thicknesses are 0.15 λ and 0.2λ and an Al-electrode thickness is 0.04 λ. The model (b) is calculated to explain the twin epitaxial film effect.

Impedance characteristics of the Lamb waves resonator propagating in X-axis (Z-X) on a Z-plane $LiNbO_3$ single crystal plate and on a twin epitaxial c-axis orientated film. Fig. 10 shows the calculated impedance characteristics of the Z-X $LiNbO_3$ single crystal plate and the twin epitaxial film indicated by solid and broken lines, respectively. The horizantal and vertical scales show a velocity and an relative impedance of the resonators, respectively. The Z-X $LiNbO_3$ single crystal plate one has spurious response due to the SH_0 mode, but the Z-X $LiNbO_3$ twin epitaxial film does not have it. So, the twin epitaxial film has a merit of no spurious responses due to the SH_0 mode compared with the Z-X $LiNbO_3$ single crystal plate.

B. Measurement Results

Authors attempted to fabricate the Lamb wave resonator on a Z-X $LiNbO_3$ single crystal plate. As its plate thickness and

Table I
Euler angles in the single crystal plate and the twin film for calculation..

	Euler angle A	Euler angle B
Z·X single crystal	(0, 0, 0)	(0, 0, 0)
Z·X twin film	(0, 0, 0)	(0, 0, 180)
Z·Y single crystal	(0, 0, 90)	(0, 0, 90)
Z·Y twin film	(0, 0, 90)	(0, 0, 270)

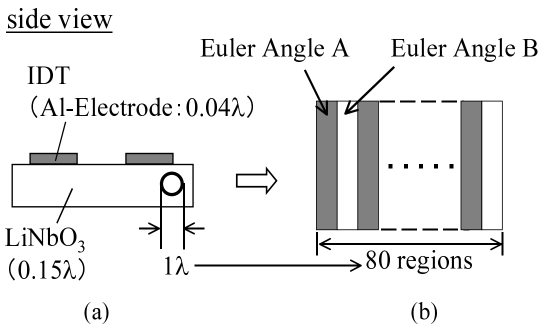


Fig9. Models for calculation of (a) actual plate and (b) enlarged plate.

λ are thick and large as 400 μm and 200μm, respectively, the resonant frequency is low as 6 MHz though the normalized thickness is 0.2λ. However, the velocity is high as 12,000m/s. Where the IDT pair, the aperture, and the each reflectors of the one-port resonator are 10 pairs, 20 λ, and 20 fingers, respectively. Fig.11 shows impedance characteristics of the resonators composed of the $LiNbO_3$ crystal plate of the 0.2 λ thickness and the twin epitaxial film of the 0.15 λ thickness by solid and broken lines, respectively, as the function of velocity. The resonators composed of the twin epitaxial film does not have the sprious response due to the SH_0 mode though that of crystal plate has it as well as the simulation results. Though the normalized thickness and the velocity of the single crystal are different from those of the epitaxial film, the results of Fig.11 are almost same as them of Fig.10.

VI. Conclusion

Authors have attempted to realize a high frequency device by using Lamb wave propagating on a thin Z-X $LiNbO_3$ film deposited by CVD having a high velocity and a large electromechanical coupling factor. The thin film deposited by CVD was a high c-axis orientated twin epitaxial one. The authors have fabricated a one-port resonator composed of an Al-electrode/thin twin epitaxial $LiNbO_3$ film/air-gap/base-substrate structure. As a result, the author realized a 4.5 GHz high frequency Lamb wave resonator with a high velocity of 14,000 m/s, a large impedance ratio of 52dB, and a wide bandwidth of 7.2 %, and without spurious response due to the SH_0 mode. Authors clarified theoretically and experimentally that the Lamb wave resonator on the twin epitaxial $LiNbO_3$ films does not have spurious response due to the SH_0 mode, though one on the crystal plates have. This resonator is not sufficiently optimized. So, it is considered that more excellent characteristics would be realized by optimizing sufficiently the electrode design.

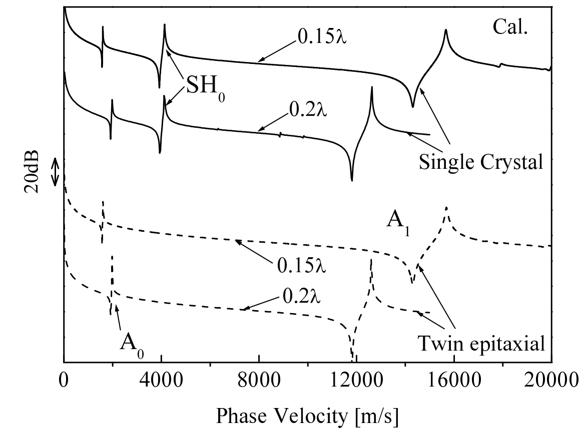


Fig10. Calculated impedance characteristics on the Z-X $LiNbO_3$ single crystal plates and twin epitaxial films (0.15λ and 0.2λ thickness).

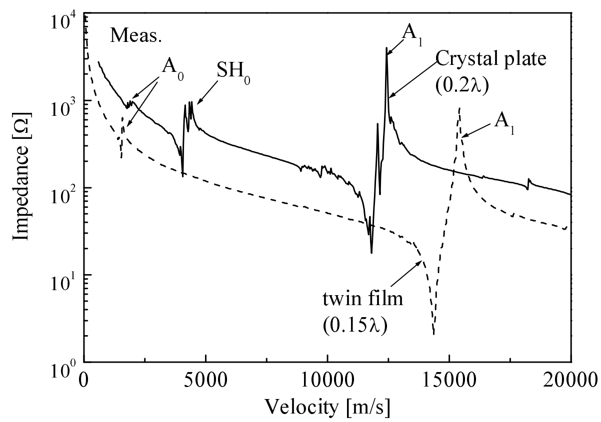


Fig11. Measured impedance characteristics of Z-X single crystal plate (0.2 λ thickness) and twin epitaxial film (0.15 λ thickness).

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