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k_{33}^2 evaluation of thin films via piezoelectric stiffening by using ultrasonic reflectometry

Motoshi Suzuki[1, 2‡], Yohkoh Shimano[1, 2], and Takahiko Yanagitani[1, 2*]
([1]Waseda Univ.; [2]ZAIKEN)

1. Background

The electromechanical coupling coefficient k_{33}^2 of a piezoelectric thin film is one of the most important indicators of the performance of RF filters and piezoelectric devices. This value can be calculated from the measured flux density constant sound velocity V^D and electric field constant sound velocity V^E of the piezoelectric material. So far, our group has successfully measured the V^D and V^E sound velocities of bulk ZnO single crystals using the Brillouin scattering method. We have also reported the evaluation of the electromechanical coupling coefficient k_{33}^2 using this method[1,2].

In contrast, in this study, we considered extending the same principle to k_{33}^2 evaluation of piezoelectric thin films. Previously, Liang et al. showed that by using the phase difference of lens echoes in ultrasonic microscopy, it is possible to measure the stage of a thin film, i.e., to evaluate the sound velocity if the thickness is known[3].

Kushibiki and Arakawa also reported a method to evaluate the acoustic wave velocity of a thin film from the phase of the reflected signal by measuring reflectance using plane wave ultrasound[4,5]. In this study, aiming to evaluate thin films in the GHz band, we used a structure in which the piezoelectric thin film to be measured was deposited directly on the back surface of the ultrasonic transducer, instead of using a water or salol coupler with large attenuation. We propose a method to estimate the acoustic wave velocity of the thin film by measuring the reflectance using this structure. Furthermore, the phase of the reflected signal is used to estimate the V^D and V^E sound velocities, and the evaluation of k_{33}^2 is attempted.

2 Methods

2.1. V^D evaluation Method

The evaluation method of V^D is explained. First, the insertion loss of the sole transducer is measured as shown in **Fig. 1** (a). Next, the piezoelectric thin film to be measured is deposited on the backside of the transducer as shown in Fig. 1 (b), and the insertion loss of the entire structure is measured. The phase of the insertion loss of the entire structure (b) is then subtracted from the phase of the insertion loss (a).

The phases of the insertion loss (a) and (b) were calculated using Mason's equivalent circuit model, and the theoretical phase difference between the two structures was obtained. In the structure (b), the phase of the reflected signal is delayed by the addition of the thin film material under test, so that V^D can be estimated when the film thickness is known. In this method, a calibration curve showing the relationship between sound velocity and phase difference at one frequency is created by simulation. Finally, the V^D is obtained by comparing the calibration curve with the measured value.

2.2. k_{33}^2 evaluation method

Next, we explain how to calculate k_{33}^2 by estimating V^E. First, a structure with a piezoelectric thin film deposited on the backside of the transducer as shown in Fig. 1 (b) or (c) is fabricated. In the state of (b), the thin film to be measured is in the open-circuit and hardened by the piezoelectric effect, so the velocity is V^D. On the other hand, in the state shown in Fig. 1 (c), the thin film is in the short-circuit and no piezoelectric hardening occurs, resulting in V^E. This time, as with the V^D evaluation method, V^E is obtained by determining the phase difference of insertion loss between the two states under different electrical conditions and comparing it to the calibration curve calculated using Mason's equivalent circuit model.

Then, using V^D and V^E, the k_{33}^2 of the piezoelectric thin film is evaluated from equation (1).

$$k_{33}^2 = 1 - \left(\frac{V^E}{V^D}\right)^2 \qquad (1)$$

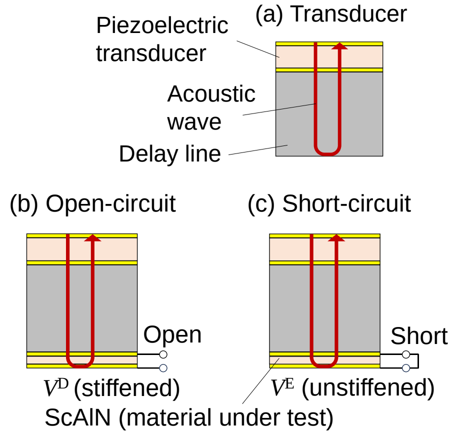

Fig. 1 (a) Sole transducer structure.
(b) The material under test in the open-circuit.
(c) The material under test in the short-circuit.

3 Results

We attempted to evaluate the acoustic velocity of a ScAlN thin film. First, to obtain a value of V^D, echoes were measured before (a) and after (b) the ScAlN thin film was deposited on the backside of the delay line. After calculating the phase difference ((a)-(b)) (**Fig. 2**), V^D = 8400 m/s was obtained by comparing the theoretical relationship between acoustic wave velocity and phase difference (**Fig. 3**).

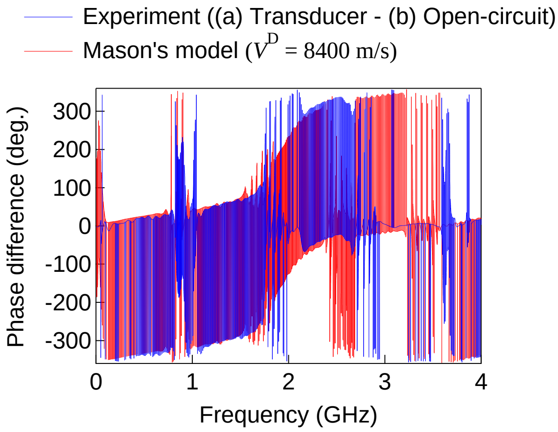

Fig. 2 Phase difference between the transducer (a) and the structure with material under test on the backside of the substrate (b).

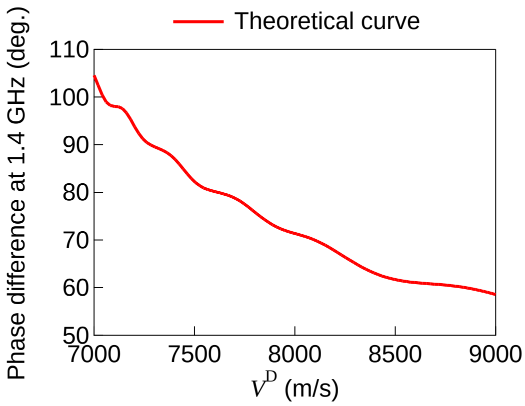

Fig. 3 The relationship between V^D and phase difference of the material under test at 1.4 GHz

Additionally, to obtain V^E for V^D, we compared the phase difference between the echoes of two different circuits (Fig. 1 (b) and (c)) and the theoretical curve. V^E was estimated to be 7900 m/s. Finally, from V^D and V^E, the k_{33}^2 of the ScAlN thin film was estimated to be 11.4%. This value is reasonable compared to the reference value of 11.9 %[6,7] for ScAlN.

4 Conclusion

We proposed a method for evaluating V^D, V^E and k_{33}^2 of piezoelectric thin films by measuring the reflectance. This method can estimate V^D, V^E and evaluate k_{33}^2. As a result, V^D = 8400 m/s, V^E = 7900 m/s, and k_{33}^2 = 11.4% in ScAlN was estimated.

E-mail: ‡motoshiorin9283@fuji.waseda.jp,
*yanagitani@waseda.jp

Acknowledgment

This work was supported by JST A-STEP (No. JPMJTR231C).

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