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Development of a Measurement Method of Bulk Acoustic Wave Properties for Thin Films by Ultrasonic Microspectroscopy Technology

Yuji Ohashi[1†], Jun-ichi Kushibiki[1], Kentaro Totsu[1], Shigeharu Matsumoto[2], Takanori Shirai[2], Yosuke Inase[2], Hiroaki Takeno[3], and Takahiro Ito[3]
([1]Tohoku Univ., [2]Shincron Co., Ltd., [3]GEOMATEC Co., Ltd.)

1. Introduction

Mobile communication systems starting with the fifth generation (5G) have begun to use frequency bands above 5 GHz, and there is an urgent need to develop elastic wave filters for the SHF band. So far, surface acoustic wave (SAW) devices, thin film bulk wave resonators (FBARs), solidly mounted resonators (SMRs), etc. have been used as acoustic wave filters. Recently, an example of successful excitation at 7 GHz in the fundamental mode has been reported using an SMR structure of a 36°Y-$LiNbO_3$ single crystal substrate/acoustic multilayer film/support substrate.[1)] To improve the excitation efficiency of the SMR, it is essential to develop an acoustic Bragg reflection multilayer film with high reflectivity and low loss. To this end, it is important to have a technology that can accurately evaluate the acoustic properties of the thin films that make up the acoustic multilayer film.

The authors have been developing ultrasonic microspectroscopy (UMS) technology and pioneering material evaluation methods using it.[2-4)] Among the UMS technologies, the plane-wave ultrasonic material characterization (PW-UMC) system is useful for evaluating the acoustic properties of bulk waves.[4)] However, until now, methods for evaluating the bulk wave acoustic properties of thin films using the PW-UMC have not been sufficiently investigated.

Therefore, in this paper, we proposed a measurement method to extend the PW-UMC to the evaluation of bulk wave acoustic properties of thin films, and conducted a theoretical study.

2. Calculation model

Fig. 1 shows the concept of measuring the bulk wave acoustic characteristics of a substrate with a thin film using the PW-UMC system. The basic measurement principle of the PW-UMC system is detailed in reference.[4)] Consider an acoustic transmission line with media #1 to #4 as shown in Fig. 1. When the sample is irradiated with a plane

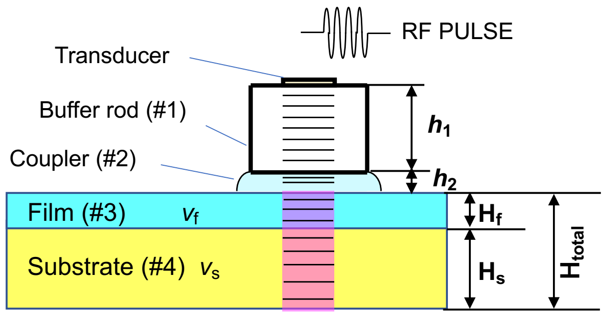

Fig. 1 Configuration of bulk wave velocity measurement for a thin film on a substrate using the PW-UMC system.

wave excited by an RF burst pulse, the amplitude and phase of the reflected wave $\mathbf{V}_2$ from the sample surface and the reflected wave $\mathbf{V}_4$ from the back surface of the sample are measured. Using the phase difference φ between $\mathbf{V}_4$ and $\mathbf{V}_2$, the total bulk wave velocity v_{total} of the film-coated substrate can be obtained from the following equation.

$$v_{total} = -\frac{2\omega H_{total}}{\phi - \pi} \qquad (1)$$

At this time, $\mathbf{V}_2$ and $\mathbf{V}_4$ are affected by the reflection coefficient and transmission coefficient caused by interference of multiple reflections within the thin film on the sample surface. When calculating, consider the effects of multiple reflections within the thin film on changes in the amplitude and phase of $\mathbf{V}_2$ and $\mathbf{V}_4$. A similar method can be used when measuring with the film surface on the back side.

3. Result and Discussion

According to the calculation model, we calculated the frequency dependence of the total longitudinal wave velocity v_{total} for a structure with SiO_2 glass film and Ta_2O_5 film on a 2 mm thick Z-cut Quartz (CQZ) substrate with the film thickness ranging from 0 to 15 µm. Figures 2 and 3 show the results of the calculations. The parameters used in the calculation are shown in Table 1.

E-mail: †yuji.ohashi.b8@tohoku.ac.jp

Table 1 Parameters used for simulation.

Material	Density (kg/m^3)	Velocity (m/s)	Z ($\times 10^6 kg/m^2s$)
CQZ [5]	2648.67	6319.37	16.74
SiO_2 [6]	2199.8	5929.1	13.04
Ta_2O_5 [7]	6880	4396.7	30.25

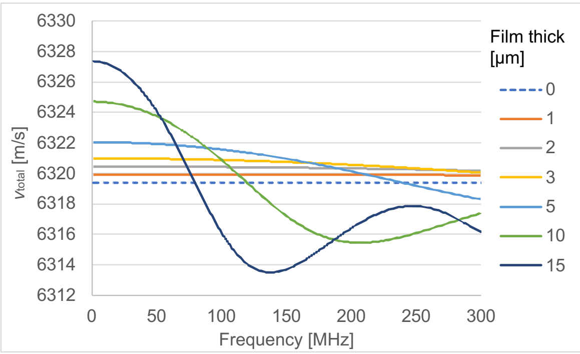

Fig. 2 Calculation results of v_{total} for SiO_2 glass film on Z-cut quartz substrate with 2 mm thick.

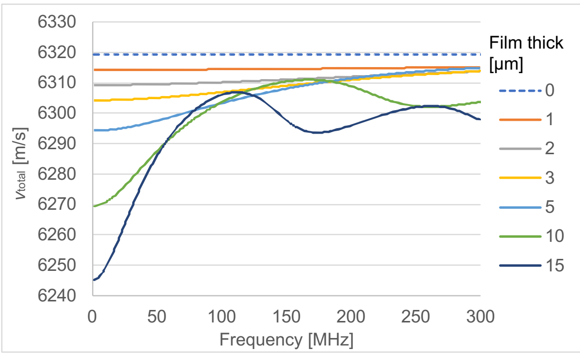

Fig. 3 Calculation results of v_{total} for Ta_2O_5 film on Z-cut quartz substrate with 2 mm thick.

In Figs. 2 and 3, the case where the film thickness is 0 μm is shown by the dotted line, which corresponds to the longitudinal wave velocity of the CQZ substrate. On the low frequency side (below 50 MHz), v_{total} increases due to the SiO_2 film, and on the high frequency side, it tends to decrease compared to the velocity of CQZ. On the other hand, in Fig. 3, on the low frequency side (50 MHz or less), v_{total} tends to decrease due to the Ta_2O_5 film, and on the high frequency side, it tends to increase to approach the velocity of CQZ. As can be seen from Table 1, the longitudinal wave velocity of CQZ is larger than those of SiO_2 glass and Ta_2O_5. However, when compared in terms of acoustic impedance Z, SiO_2 glass is smaller than CQZ, but Ta_2O_5 is larger than CQZ. From these, the results shown in Figs. 2 and 3 can be interpreted as follows. When the frequency is infinite, the film thickness is sufficiently thick compared to the wavelength, so the convergence value of v_{total} is considered to be coincide with the average velocity simply calculated from the propagation times in the substrate and film. The velocity of SiO_2 glass and Ta_2O_5 is slower than that of CQZ, which is why the calculated values on the high frequency side tend to be lower than the velocity of CQZ. Furthermore, the periodic fluctuations seen in the results in Figs. 2 and 3 (particularly noticeable when the film is thick) are thought to be due to phase changes due to interference caused by multiple reflections within the film. Since the sign of the reflection coefficient at the film-substrate boundary is reversed depending on the acoustic impedance relationship between the film and the substrate, it is expected that the influence on the phase change will be reversed between the SiO_2 glass film and the Ta_2O_5 film. Indeed, when looking at the velocity on the low frequency side, it can be seen that in the case of the SiO_2 glass film in Fig. 2, it fluctuates toward faster velocities, whereas in the case of the Ta_2O_5 film in Fig. 3, it fluctuates toward slower velocities.

4. Summary

In this paper, we proposed a method for measuring the bulk wave acoustic properties of thin films using the PW-UMC and conducted a theoretical study. From the results of theoretical calculations, it was found that characteristic velocity changes occur in the frequency dependence of the total bulk wave velocity. It is expected that this feature can be used to estimate thin film parameters (velocity, density, film thickness). In the future, we will proceed with experimental studies.

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