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Liquid Viscosity Measurement Using Shear Horizontal Wave Propagation in Piezoelectric Ceramic/Liquid/Glass Trilayer

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1. INTRODUCTION

There has been a growing interest in the use of an acoustic wave device for application such as gas [1], mass [2,3], and liquid sensing [4]. In the device construction as a microsensor operating in liquid environment, it is essential to evaluate the liquid properties such as viscosity [5], density [6] and conductivity [7]. For the above purpose, the acoustic wave device requires low energy loss into a liquid layer. Rayleigh and Lamb wave devices immersed in viscous liquid media suffer high propagation loss at a solid/liquid interface via the mode conversion to the longitudinal wave in the liquid. Recently, much interest has been focused on the use of a shear horizontal (SH) wave for liquid sensing. The SH wave device has the advantage of low energy loss at a solid/liquid interface.

In this paper, the propagation characteristics of SH waves in a piezoelectric ceramic/liquid/glass trilayer are described through the numerical calculation and experiment. Mechanical displacement distributions of the SH wave in the trilayer are strongly dependent on the thickness of the liquid layer and the liquid viscosity. The device used for the experiment need a small amount of liquid sample compared with that in a commonly-used rotational viscous meter. Theoretical temperature dependence of viscosity (silicon oil) is successfully compared to the measured result. This method has the advantage of stable measurement because of the sandwiched liquid medium.

2. NUMERICAL ANALYSIS

Figure 1 shows a coordinate system to calculate the propagation characteristics of SH wave in a trilayer structure composed of a piezoelectric ceramic thin plate, a liquid layer (Silicon oil) and a glass plate. The origin ($X_3 = 0$) is considered as the interface between the piezoelectric thin plate with a thickness d, and the liquid layer with a thickness $r_1 d$ ($0 \le r_1 \le 1$). Numerical calculation of the phase velocity of the SH wave in the trilayer structure is carried out by developing the Farnell's method [8].

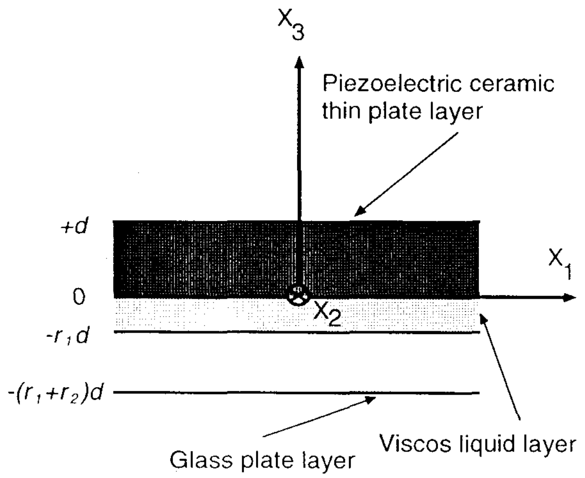

Fig.1 Coordinate system used in numerical analysis.

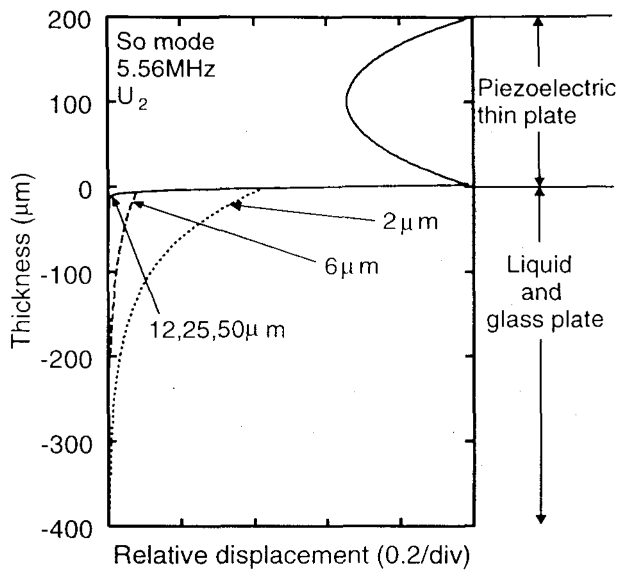

Fig.2 Relative displacement distributions of U_2 in trilayer for various thicknesses of liquid layer. Calculations are performed for S_0 mode with carrier frequency of 5.56MHz

Figure 2 shows relative displacement distributions of U_2 of the S_0 mode SH wave in the trilayer for various thicknesses of the liquid layer. The calculated results correspond to the carrier frequency of 5.56 MHz. Dotted and broken curves for the cases of 2 μm-thick and 6 μm-thick silicon oil layers indicate that the displacements of the S_0 mode penetrate into the glass plate beyond the silicon oil layer. On the other hand, the displacement of the SH wave completely decays in the silicon oil layer thicker than 12 μm and does not exist in the region of the glass plate.

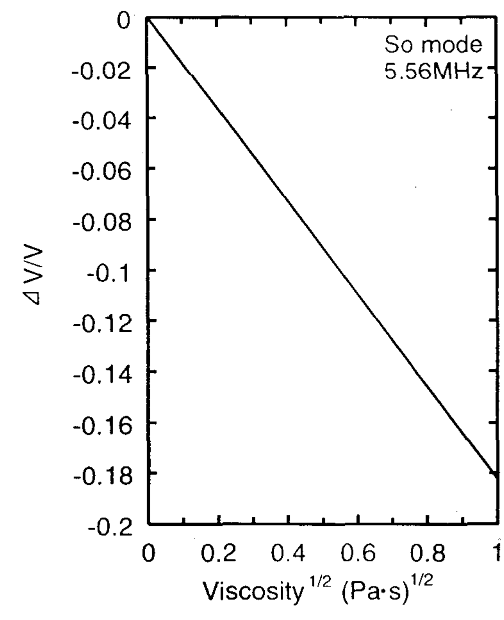

Fig.3 Fractional velocity change of S_0 mode of SH wave as function of viscosity. Calculation is performed at for frequency of 5.56MHz

The calculated fractional velocity change as a function of viscosity is shown in Fig. 3 corresponding to the S_0 mode of SH wave with the frequency of 5.56 MHz, which decreases linearly as the square root of viscosity. This result suggests the usefulness of viscosity measurement by using the S_0 mode of SH wave.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 4 shows a schematic construction of the SH wave device prepared for this study. A silicon oil (Shin-Etsu, KF96-100) is sandwiched between a 230 μm-thick piezoelectric ceramic plate (TDK, 101A) and a 400 μm-thick glass plate (Corning, 7059). The thickness of the silicon oil layer is 25 μm, adjusted by PET film for spacer. This device needs a small amount of liquid sample with the capacity of about 0.003 ml. Two interdigital transducers (IDTs) are mounted on the piezoelectric ceramic thin plate, each of which has seven electrode-finger pairs and 400 μm interdigital periodicity. The device is contained in a controllable temperature bath.

Measured frequency dependences of the insertion losses of the SH wave device are shown in Fig. 5 for two cases corresponding to the device without and with silicon oil, represented by real and dotted lines, respectively. The difference of the insertion losses in the two cases is substantially omitted. This result indicates that the SH wave does not suffer from the propagation loss at the solid/liquid interface. It is also obvious that the center frequency of S_0 mode is 5.56 MHz, being equal to the frequency in Fig. 2 and 3.

Figure 6 shows temperature dependences of the phase change of the delay device. The phase change is measured via a network analyzer (HP, 4195A) while the temperature is kept by a temperature controller (Shimaden, FP21) over the range from 30 to 90 °C. The viscosity and density of silicon oil used for the evaluation are dependent on the temperature, where the viscosity change is from 0.097 to 0.038 Pa.s, and the density change is from 963.04 to 915.10 g/cm^3. The numerical calculation result represented by real line based on the data in a technical report on Shin-Etsu Silicon. The change of phase delay of the S_0 mode propagation between the two IDTs shows an almost linear behavior with temperature. The experimental results are in good agreement with the numerical calculation.

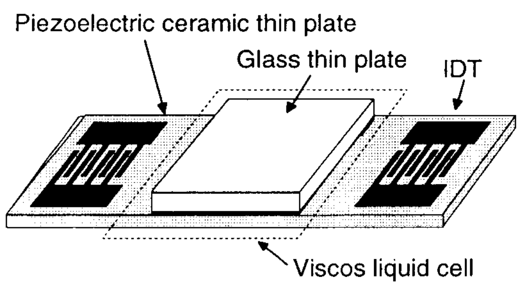

Fig.4 Schematic construction of device prepared for experiment.

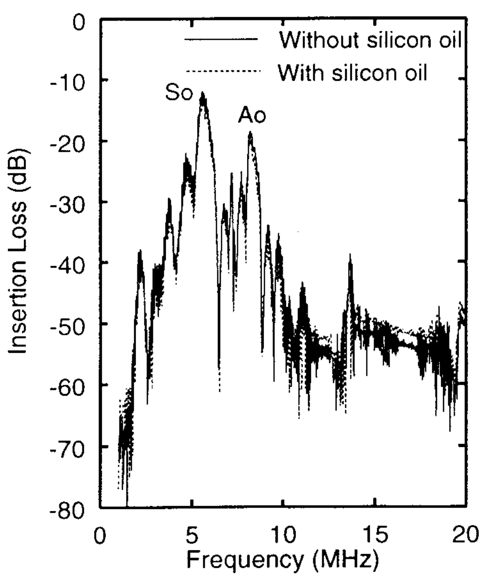

Fig.5 Frequency dependences of insertion losses of SH wave device. Real and dotted lines correspond to insertion losses of device with and without silicon oil, respectively.

4. CONCLUSION

A viscosity measurement method of liquid (silicon oil) was evaluated. Propagation characteristics of SH wave in a piezoelectric ceramic/liquid/glass trilayer was numerically analyzed. The measured temperature dependence of the viscosity of silicon oil is good consistency with numerical analysis results. This technique has the advantage of low energy loss, small amount of liquid sample and stability of liquid sample.

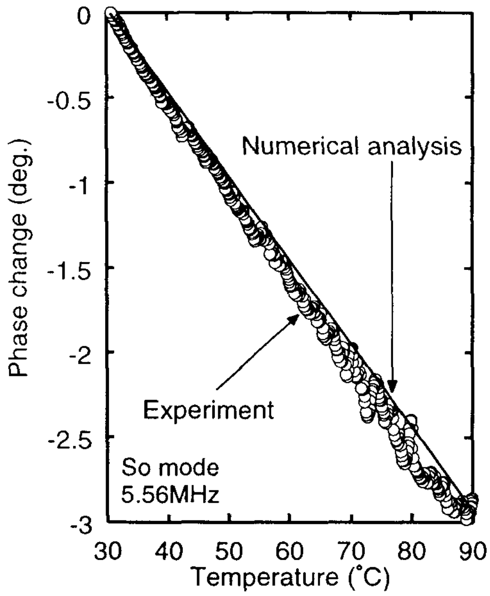

Fig.6 Temperature dependences of phase change of delay device. Real line and open circles are for numerical calculation and experimental results, respectively.

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