Liquid Density Sensing Using a FPW Resonator in PZT/SiN$_x$ Membrane

JYH-CHENG YU* and Huang-Yao Lin

Department of Mechanical and Automation Engineering
National Kaohsiung First University of Science and Technology
2, Juoyue Rd., Nantz District, Kaohsiung 811, Taiwan, R.O.C.

Abstract

A Flexure Plate Wave (FPW) resonator using piezoelectric lead zirconate titanates (PZT) films is proposed for liquid density sensing. FPW device is suitable for liquid sensing because of less scattering of the energy from the FPW to the loading liquid due to its low phase velocity. This study adopts Sol-Gel derived PZT thin films to fabricate the FPW resonator. The material system is Pt/Ti/PZT/LSMO/SiN$_x$. The COM theory is used to simulate the response of a two-port SAW resonator, which is extended to the design of the FPW resonator. The preliminary measurement results show that the resonant frequency and the relative liquid density have a good linear correlation, and demonstrate the feasibility of the sensor application using the FPW resonator. The influence of the liquid viscosity to the frequency deviation is also investigated.

Keywords: FPW resonator, Flexure plate wave, PZT, Sol-Gel, Liquid density sensing

1. Introduction

Lamb wave[1] are associated with Rayleigh waves on a thin plate whose thickness is smaller than the wavelength. They can be considered as two Rayleigh waves propagating on both sides of a plate. Two kinds of waves can propagate through the plate independently, namely the symmetric and the antisymmetric waves. The A_0 wave is the antisymmetric Lamb wave with the lowest velocity. The low operating frequency is an attractive feature as it implies relatively inexpensive associated electric circuit. This feature makes the wave suitable for liquid sensing due to the A_0 wave does not excite compressional waves in a loading liquid if its phase velocity is lower than the sound velocity of liquid. The back cavity of the FPW device can serve as the loading area of the sensing liquid.

Acoustic wave sensors used to be realized on a bulk piezoelectric substrate. Piezoelectric thin films, such as PZT, Zinc Oxide (ZnO), and Aluminum Nitride (AlN), have the cost advantage over crystal materials. Among them, the electromechanical coupling effect (K^2) of PZT is three to nine times and the dielectric constant 100 times over AlN and ZnO. Therefore, PZT is potentially suitable for thin film acoustic sensors.

Many researches address the application of Lamb wave sensors in chemical and liquid sensing. Laurent *et al.*[2] presented the theoretical modeling of FPW devices using AlN and ZnO, and compared with the experiments of liquid loading. Costello *et al.*[3] proposed the FPW device with ZnO for the viscosity sensing. Weinberg *et al.*[4] derived the fluid-damping model of the FPW device with AlN. To increase the differentiability of the resonant frequency shift, reflecting gratings are added to the Lamb wave device that is first reported by Joshi[5]. Nakagwa [6] also adopted the same configuration but applied to a AT-cut quartz substrate.

This study will develop the FPW delay line and the FPW resonator using the structure of PZT on the silicon

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*Corresponding author: jcyu@ccms.nkfust.edu.tw

nitride membrane. We will discuss the design of the reflecting grating using the COM (Coupling of Modes) theory, and apply to the FPW devices. The liquid density will determine the non-viscous liquid loading when the device cavity is filled up with liquid. Finally, we will research the application feasibility of the FPW resonator for liquid density sensing.

2. The Fabrication of the FPW Resonator

Fig 1 shows the fabricating procedure of the FPW resonator that includes the coating of PZT film, the silicon etching, and the lift-off of IDT. The materials system consists of Pt/Ti/PZT/LSMO/SiN_x. First, we deposit the SiN_x (1.2μm) by LPCVD as the mask layer and the membrane structure on the (100) silicon substrate. Then the LSMO and the PZT thin films are coated by sol-gel method. The LSMO layer is used as a buffer layer between PZT and SiN_x to enhance the piezoelectric characteristic and avoid the crack of PZT. The electrode consists of Pt and Ti is patterned using lift-off techniques. Next, the back cavity is patterned on SiN_x using RIE. Finally, the membrane cavity of the device is fabricated using KOH anisotropic etching.

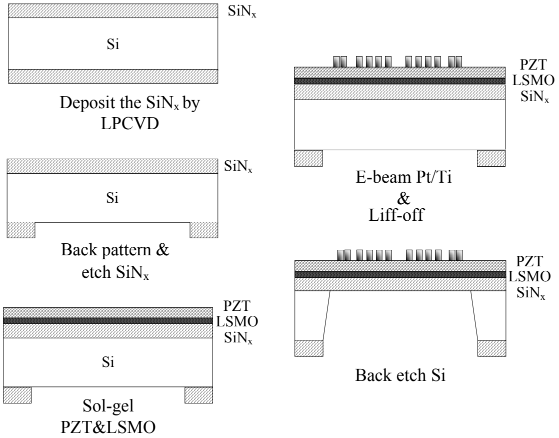

Fig 1 A schematic view of the fabricating process

3. The Modeling of SAW Resonators and FPW Wave Sensors

This section applies the COM theory to simulate the two-port SAW resonator over a bulk PZT. The spacing between the relating grating and IDT is designed to increase the response at the resonator frequency. Fig 2 shows the simulation result of the proposed design. The resonator design will be applied the FPW device, but the resonant frequency will be determined by the phase velocity of FPW.

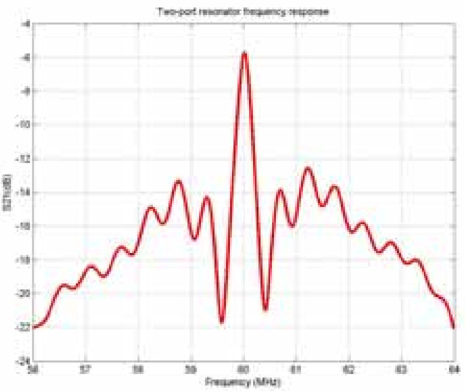

Fig 2 Two-port saw resonator frequency response

Consider the A_0 mode of FPW propagating on a thin plate; he phase velocity of the plate regime subject to a tensile stress and liquid loading can be well approximated by the simple asymptotic expression[7]:

$$v_P = \left(\frac{T_x + B}{M + \rho_F \delta_E + M_\eta} \right)^{1/2} \tag{1}$$

where T_x is the component of in-plane tension in the x direction,

$\rho_F \delta_E$ is the mass effect,

ρ_F is the density of the fluid, and

M_η is the viscosity effect.

$$\delta_E = \left(\frac{\lambda}{2\pi} \right) \left[\left(1 - \frac{v_P}{v_F} \right)^2 \right]^{-1/2} \tag{2}$$

$$M_\eta = \frac{\rho_F \delta_V}{2} \tag{3}$$

where $\delta_V = \left(\frac{2\eta}{\omega \rho_F} \right)^{1/2}$ is the viscous decay length,

ω is the operating angular frequency, and

η is the shear viscosity.

3.1. The loading effects for a non-viscous liquid

When the FPW device is in contact with a loading liquid, the phase velocity will be influenced by the mass effect ($\rho_F\delta_E$) that can be determined by the evanescent decay length. When the liquid thickness is larger than the evanescent decay length, the mass-loading effect of the liquid will remain the same as shown in

Fig 3. The mass sensitivity and tension sensitivity of the perturbation of phase velocity are as follows:

$$\frac{\Delta v_p}{v_p} = s_m \times \rho_F + s_T \times T_x \tag{4}$$

where $s_m = -\dfrac{\delta_E}{2(M + \rho_F \delta_E)}$,

$$s_T = \frac{1}{2(T_x + B)}$$

In our case, s_m =-2.78(m^2/N) and s_T =7.69*10-5(m/N). The tension effect due to the liquid pressure can be ignored when compared with the bending stiffness. Therefore, when the device cavity is filled up with different liquids, the change of the phase velocity will be related to the density of the liquid and thus can be used as a density sensor.

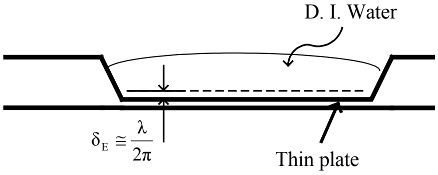

Fig 3 The evanescent decay length for the liquid loading in a FPW device

3.2. The loading effects for a viscous liquid

From Eq.(1), we know that the phase velocity of FPW will be influenced by fluid density (ρ_F) and shear viscosity (η) of the loading liquid. However, we can't differentiate the velocity perturbations between liquid density and viscosity because the density and viscosity are coupled in the viscous effect as seen from Eq. (3). In another word, the liquid viscosity can't be determined by the frequency shift. Thus, we focus on the density sensing for non-viscous liquids in the following study. However, we will also study the viscosity effect by comparing two different liquids with the same density.

4. Experimental Results and Discussions

4.1. The FPW delay line and the FPW resonator signals

The frequency responses of the FPW delay line and the FPW resonator are shown in Fig 4. The calculated resonant frequency of the A_0 mode is about 5.88 (MHz) that is close to the experimental results for the FPW delay line of 5.47 and the FPW resonator of 5.53 (MHz). The difference between the theoretical and experimental results might be due to the application of the material properties of bulk PZT in the estimation because the film properties are not available. As expected, the FPW resonator (-16.5 dB) has a lower insertion loss than the FPW delay line (-23.4 dB).

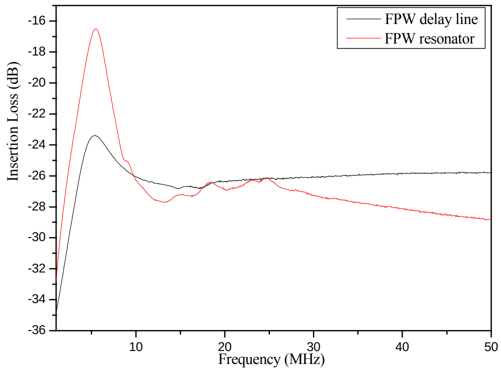

Fig 4 The S_{21} frequency response of the FPW devices

4.2. Liquid sensing using the FPW delay line and the FPW resonator

4.2.1. The density sensing for non-viscous liquids

The measurement results are shown in Table 1. We summarize the different density effects for the theoretical and experimental results in Fig 5. The experimental results of the resonant frequency vary linearly with liquid density, which shows the potential for density sensing, but there is a static difference between the theoretical and the experimental results. The static difference may be due to liquid damping and stress effects that are presumed negligible.

Table 1 The resonant frequency and insertion loss of the devices loaded with non-viscous liquids

	Theoretical	Experimental	
	Frequency (MHz)	Frequency (MHz)	Insertion Loss (dB)
IPA	4.94	5.23	-31.09
Water	4.75	5.17	-29.43
Saline solution	4.59	4.98	-33.38

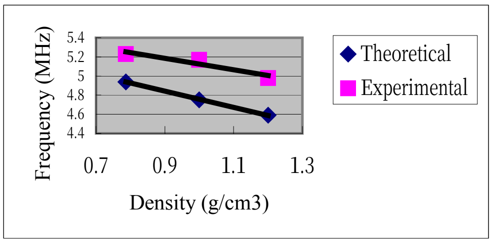

Fig 5 The sensitivity analysis between the resonant frequency and the density for non-viscous liquids

4.2.2. The frequency deviation due to liquid viscosity

Here, we compare two liquids, glycerol and saline solution with the same density to study the viscosity effect. From Table 2, we observe that the glycerol loading will introduce additional frequency deviation compared with the saline solution with the same density. Also, the viscosity effect of glycerol will cause more damping effect than the saline solution and increases the insertion loss.

Table 2 The comparison between viscous and non-viscous liquids with the same density

	Theoretical	Experimental	
	Frequency (MHz)	Frequency (MHz)	Insertion Loss (dB)
Saline solution	4.59	4.98	-33.38
Glycerol	4.49	4.73	-37.04

5. Conclusions

This study has successfully fabricated the FPW resonator on the PZT piezoelectric thin films and compared with the modeling analysis. The device is applied to the loading of non-viscous and viscous liquids. We have observed that the liquid loading will increase the insertion loss and decrease the resonant frequency that is consistent with theoretical prediction. Three non-viscous liquids, DI Water, IPA and saline solution, are applied to the resonator. The results show that the resonant frequency and the liquid density have a good linear correlation despite a static difference, which demonstrates the feasibility of density sensing. To study the viscosity effect, two liquids, glycerol and saline solution with the same density are investigated. Additional frequency deviation is observed and the insertion loss is increased for viscous liquid (glycerol), which also matches fairly with the theoretical estimation.

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