The Lamb-Wave Device Using PZT Sol-Gel Thin Film for Mass-Loading Sensing

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Abstract

This study presents a Lamb-wave (Flexural Plate Wave, FPW) sensing device using the structure of PZT thin film on silicon membrane. A well-designed FPW device will have less energy dissipating into the sensing fluid and thus is suitable for biosensing. This research adopts the Sol-Gel method to prepare the piezoelectric thin films of lead zirconate titanates (PZT). The propagating membrane for FPW is fabricated using KOH etching. The thickness of the PZT thin films is about 0.6 (μm) and the thickness of the Si membrane is 20 (μm). The periodicity of the IDT is 100 (μm). The delay line is applied to detect the phase deviation due to the loading mass and the change of ambient temperature. The results show a linear relationship between the phase deviations and these measurands, and demonstrate the feasibility of sensor application.

Keywords*:* Lamb wave, Flexural Plate Wave, PZT
Subject Category: Actuators and Mechanical/Physical Sensors, Biomedical and Chemical Devices

1. Introduction

The success of acoustic devices in signal processing leads to the popular research interest of acoustic sensors especially in the areas of mechanical and biochemical sensing. The operation principle of acoustic-wave sensors is simple. The velocity and the attenuation of an acoustic wave propagating in a solid substrate are affected by the surface state of the substrate. The changes in the surface state due to adsorption of molecules or liquid loading will be measured by the acoustic losses, the phase deviation, and the oscillation frequency using an oscillator set-up [1].

Most acoustic sensors employ surface acoustic wave (SAW) as their primary transduction mechanism[2]. This mode of propagation will confine the acoustic energy to very near the surface of an isotropic solid, and is most conveniently excited on a piezoelectric single crystal, such as quartz (SiO_2), lithium tantalate ($LiTaO_3$), and lithium niobate ($LiNbO_3$), using an interdigital transducer (IDT) [3].

If the thickness of the conducting substrate is smaller than the wavelength of the acoustic wave, Lamb waves (also called flexural plate wave) can be excited [4]. There are several advantages of Lamb wave sensors over SAW sensors in the applications of chemical sensing. A slow mode of propagation, such as the lowest antisymmetric mode A_0, will minimize the radiation loss in liquid sensing. The access to the backside of the etched membrane can also facilitate the isolation design of the transducer from loading liquid.

Earlier researches focused on the lamb wave devices using piezoelectric

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crystals [5] and bulk ceramics. Recently, Lamb wave sensors using the structure of piezoelectric thin films on silicon have drawn lots of attentions because of the cost advantage and the possibility to integrate electronics in one chip. Most Lamb wave devices of piezoelectric thin films employ zinc oxide (ZnO) [6][7] and aluminum nitride (AlN) [8].

The piezoelectric coupling coefficient of thin films of PZT is much higher than those of AlN and ZnO, which will greatly improve the sensitivity of sensor applications. Due to the complexity of the deposition process and the material interface, few literatures[9] address the lamb wave devices using PZT thin film. Sol-gel deposition[10] is a promising method because of the cost advantage for commercial applications. This study will introduce the fabrication and the characterization of the Lamb-wave device using the structure of sol-gel PZT thin film on silicon membrane, and present the preliminary results for the device in mass-loading and temperature sensing.

2. Design and Fabrication

The device uses the design of acoustic delay lines as sketched in Figure 1. The velocity and the attenuation of the acoustic wave are affected by the surface loading of the composite membrane such as mass loading and a differential pressure.

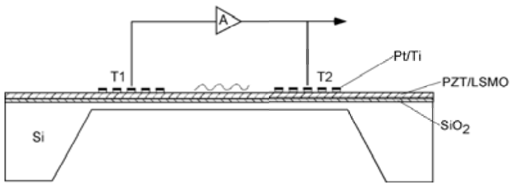

Figure 1 Schematic view of the micromachined Lamb wave sensor.

The material system of the composite membrane consists of Pt/Ti/PZT/LSMO/SiO_2/Si. The IDT design adopts a period of 100 mm, constant finger overlap, and uniform finger spacing. The variations of the finger overlap (24~30λ), the delay distance (30~56λ), and the finger pairs (15~25) are designed to study their effects on the sensor performance.

Figure 2 illustrates the fabrication procedure of the Lamb wave device. The composite membranes were first formed on a (100) silicon substrate by sequential deposition of a silicon oxide layer of 1.8 μm using wet thermal oxidation, a (La_xSr_{1-x})MnO_3 (LSMO) layer of 1500 Å, and a 0.6 μm of PZT film. The relatively thick PZT film was prepared by a sol-gel method involved multiple deposition and annealing sequences. The thin LSMO layer is used as a buffer layer between the PZT thin film and the silicon substrate, which will improve the fatigue resistance and the piezoelectric properties.

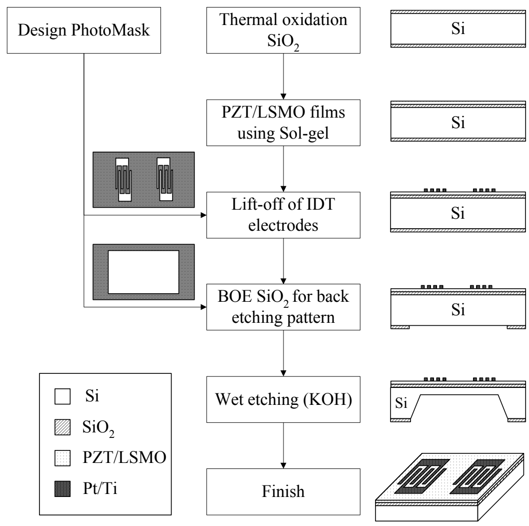

Figure 2 Fabrication procedure of the Lamb-wave device

The interdigital electrodes were patterned on the PZT surface using lift-off techniques. The materials of the electrodes consist of 150 Å of titanium and 2000 Å of platinum using E-beam. The Ti layer serves as an adhesive layer between the PZT film and the Pt electrodes. The SiO_2 mask for the backside etching is patterned using Buffered Oxide Etchant (BOE) etching, and a silicon membrane of 20~30 μm is fabricated using KOH wet etching (30wt% and 80°C). During the backside etching of silicon, a Teflon chuck is used to protect the IDT transducers and the PZT film on the front. Ultrasonic agitation has been introduced during the anisotropic etching to reduce the surface roughness and improve the etching uniformity. The average surface roughness of the etched silicon membrane is 160 Å.

3. Experimental Results and Discussions

Figure 3 presents the schematic view of the Lamb wave device in its experimental mounting fixture. The sensor was exposed to water, acetone, isopropanol, and several water-glycerol solutions. The frequency responses are measured using the network analyzer to study the effects of different liquids, loading mass, and temperature on the change of phase velocity.

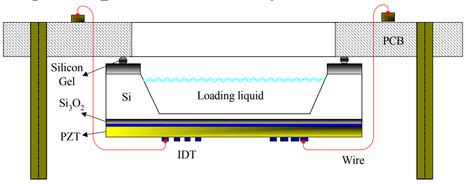

Figure 3 Schematic view of the Lamb wave device in its experimental mounting fixture.

3.1. Mass loading

Mass loading on the membrane will cause quite large velocity changes. The frequency and the phase shift due to the liquid mass. The theoretical relation between the frequency shift and the loading mass is as follows [11]:

$$\Delta f = f_{air} \frac{m_{liquid}}{2M_{plate} + m_{liquid}} \tag{1}$$

The sensitivity will increase as the thickness of the membrane decrease.

The sensor is first loaded with glycerol using a micro-dropper. The frequency responses of the device with various mass loading are shown in Figure 4. As the silicon is still relative thick (20 μm) compared with the wavelength (100 μm), there might be several modes of acoustic wave to be excited. The center frequency is thus not easy to determine from the figure. However, we can observe from the figure that the insertion loss increases and the frequency contour shifts toward the left as the loading mass increases. The tendency corresponds to the theoretical results in the literatures.

The center frequency shifts due to the loading mass, which at the mean time changes the phase velocity. The phase diagram will shift downward (increase of delay) as the loading increases. We can measure phase deviation for a particular frequency of the input signal, and use it to sense the loading. Figure 5 shows the relation between the phase deviation and the mass of loading is fairly linear. Similar tendency can be observed if the liquid is changed to water.

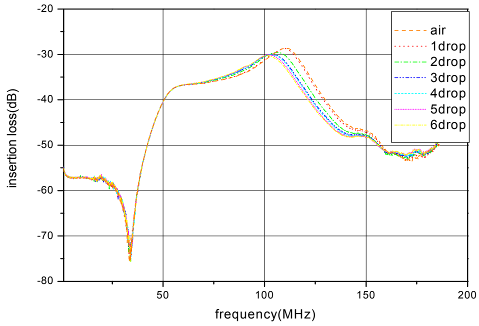

Figure 4 Frequency responses of the device with various mass loading.

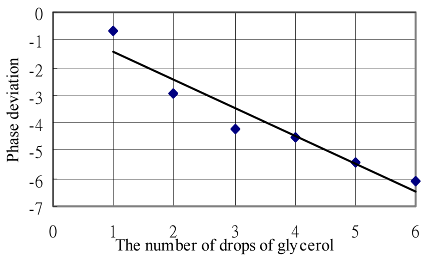

Figure 5 Phase deviation at 84 Mhz induced by the glycerol loading

3.2. Density Effect

Since water, acetone, and isopropanol are non-viscous fluids, the change of acoustic velocity depends primarily on the density of the liquid. The specific weights of acetone and isopropanol are 0.791 and 0.787 respectively. We can expect the frequency response of water will be much different from acetone and isopropanol. This tendency can be observed from the phase response shown in Figure 6.

Increasing the weight-percentage of glycerol will increase both the density and the viscosity of the solution resulting in a decreasing phase velocity and an increasing of attenuation effect. Figure 7 shows the phase deviation of the loaded solutions with different glycerol concentrations.

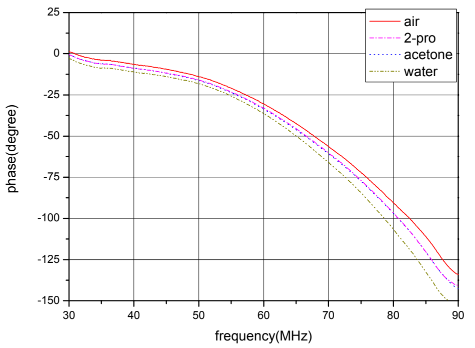

Figure 6 Phase responses of the sensor loading by various liquids

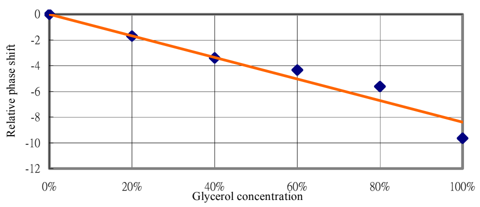

Figure 7 Dependency of the phase deviations (at 76MHz) of the glycerol/water solution to its concentration

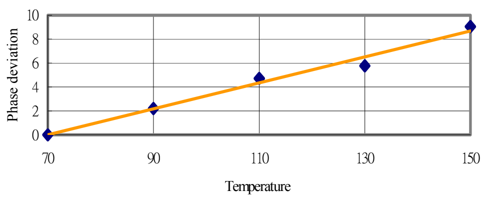

Figure 8 The phase deviation at 68 MHz at different temperatures compared with 70°C

3.3. Temperature Behavior

Temperature is an important parameter for an acoustic sensor. Figure 8 shows the dependency of the phase deviation to ambient temperature. The sensitivity reveals the possibility of temperature sensing. However, for other sensor applications, suitable compensation needs to be considered.

4. Conclusions

This study describes the design, the fabrication procedure, and the initial experimental results of a Lamb wave device using a PZT/silicon structure. The sol-gel derived piezoelectric film demonstrates promising characteristics in the application. The phase deviation is used as the sensing index for the mass loading sensitivity and the temperature behavior. The sensitivities to the addition of small amount of mass and the variation of liquid densities suggest the application feasibility for chemical and biological sensing.

Acknowledgments

The authors would like to thank the National Science Council of the Republic of China for financially supporting this research under Contract No. NSC 92-2216-E-327-001.

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