EVALUATION OF PROPERTIES OF SUB-MICROMETER THIN FILMS USING HIGH FREQUENCY ULTRASONIC WAVES

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ABSTRACT

Accurate monitoring of the thickness and elastic properties of thin films with thickness in the sub-micrometer range is very important in the area of N/MEMS fabrication. In this paper, we utilize a RF surface acoustic wave (SAW) device to measure the dispersion of SAW in a thin film deposited layered substrate first, and then, determine the elastic properties of the thin film inversely through an optimization algorithm. Firstly, we analyze the dispersion of SAW in a SiO_2/YZ-$LiNbO_3$ layered specimen and serve as the forward solution of the inverse evaluation. Secondly, a novel design of interdigital transducer pairs was proposed to measure the dispersion of SAW in such a layered specimen. To increase the bandwidth of the SAW device, slanted finger interdigital transducer (SFIT) was employed to generate wide band SAW signals. The SFIT was designed by using the coupling of modes method to ensure the best frequency response. Sub-micrometer thickness SiO_2 thin films were deposited on the piezoelectric YZ-$LiNbO_3$ substrate via the PECVD process. Pairs of the SFITs were then fabricated on the substrate. A network analyzer was used to measure the frequency response of the SFIT. The frequency responses were then processed using the spectral analysis to obtain the dispersion of SAW in such a layered specimen. With the forward solution and measured dispersion of the thin film deposited layered specimen, the elastic properties of the SiO_2 layer can be reconstructed through the using of the simplex algorithm. Result of the inversion shows that the elastic properties of the sub-micrometer thin SiO_2 film can be determined successfully. It is worth noting that results of this study can be employed to design an in-situ thin film thickness monitoring SAW sensor.

1 INTRODUCTION

Surface acoustic waves (SAW) have been used extensively in the area of nondestructive evaluation (NDE) of materials or investigation of the surface properties of materials [1,2]. Since most energy of the SAW is confined in one to two wavelength around the surface, high frequency SAW devices are very suitable to be developed as thin film sensors. In the literatures, Hickernell and his coworkers [3-8] conducted theoretical as well as experimental studies on the property measurements of a variety of thin film using SAW. In the studies, the frequency responses of SAW were measured and utilized to determine the thin film properties inversely. However, the above mentioned method can only be used to evaluate nonconductive materials. In addition, automatic determination of the various harmonic resonance modes is rather complicated if not impossible. The objective of this study is to develop a nondestructive evaluation technique suitable for not only dielectric but also metallic sub-micrometer thin films. In this paper, we proposed a novel application of Slanted Finger Interdigital Transducers(SFIT) to measure the thin film induced SAW dispersion, and then, employed an inversion algorithm to determine the thickness and the elastic properties of the sub-micrometer thin film.

2 DIPSERSION OF SAW IN SiO_2/YZ-$LiNbO_3$ LAYERED SPECIMEN

The formulation for studying the SAW propagation in piezoelectric layered media proposed by Wu et al. [9] was adopted to calculate the dispersion of SAW induced by the thin film on top of a piezoelectric substrate. Figure 1 shows the schematic picture of the SiO_2/ YZ-$LiNbO_3$ layered half space. Figure 2 is the calculated dispersion of the phase velocity. The results show that the phase velocity increased monotonically with the frequency. In addition, the thicker the SiO_2 thin film, the higher the phase velocity.

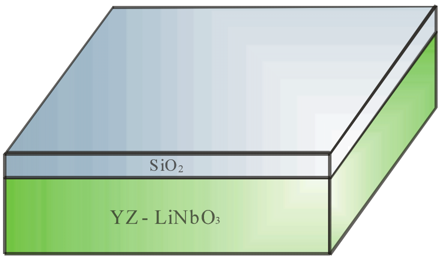

Figure 1: SiO_2/ YZ-$LiNbO_3$ layered specimen

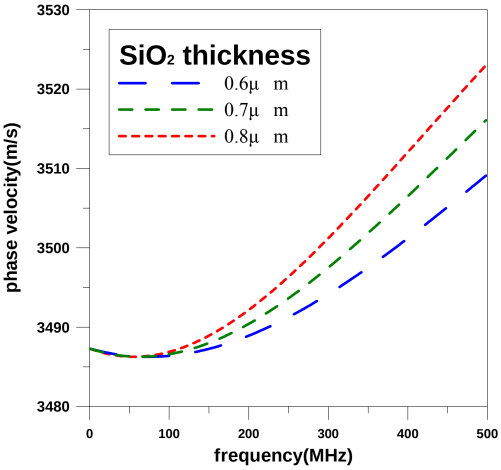

Figure 2: Dispersion relation of SiO_2/YZ-$LiNbO_3$

3 DESIGN OF SLANTED-FINGERINTERDIGITAL TRANSDUCER

As shown in Figure 3, we proposed a novel method for measuring the thin film properties using the SFIT. The advantage of using the SFIT is that a very wide frequency bandwidth can be obtained, and this enhances greatly the inversion accuracy.

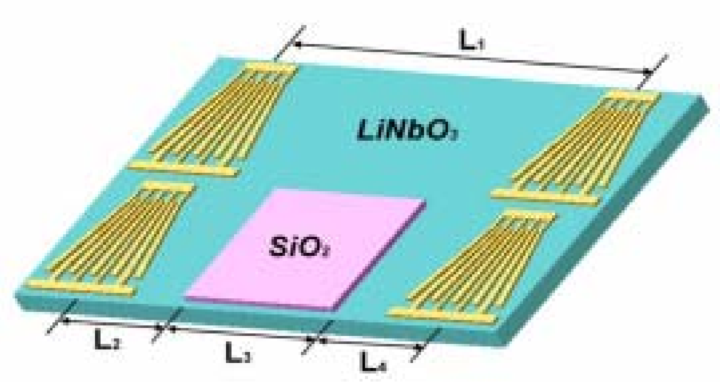

Figure 3: layout of the thin film SAW sensor

Figure 3 shows the phase difference ϕ_1 induced by the surface acoustic wave traveling through path L_1 is

$$\phi_1 = 2\pi f \frac{L_1}{V_1} \tag{1}$$

while the phase difference ϕ_2 induced by the surface acoustic wave traveling through path $L_2+L_3+L_4$ is

$$\phi_2 = 2\pi f \frac{L_2}{V_1} + 2\pi f \frac{L_3}{V_2} + 2\pi f \frac{L_4}{V_1} \tag{2}$$

where, V_1 is the phase velocity of surface acoustic wave on YZ-$LiNbO_3$, and V_2 is the phase velocity of surface acoustic wave on the SiO_2/YZ-$LiNbO_3$ layered specimen.
Let L_1 equals to $L_2+L_3+L_4$, the phase difference induced by surface acoustic wave between the two paths can easily be derived as

$$\Delta\phi = \phi_2 - \phi_1 = 2\pi f \frac{L_3}{V_2} - 2\pi f \frac{L_3}{V_1} = 2\pi f L_3 \left(\frac{1}{V_2} - \frac{1}{V_1}\right) \tag{3}$$

The phase velocity of the surface acoustic wave on the SiO_2/YZ-$LiNbO_3$ layered specimen can be obtained as

$$V_2 = \frac{1}{\left(\frac{\Delta\phi}{2\pi f L_3} + \frac{1}{V_1}\right)} \tag{4}$$

In order to enlarge the bandwidth of the wave signals, we employed the so called Slanted Finger Interdigital Transducer (SFIT) as the wave source and receiver. SFIT SAW devices could provide a frequency response with small pass-band ripple, flat and wide pass-band, large stop-band rejection, and steep cutoff characteristics. The coupling-of-mode(COM) model was used to analyze the frequency response of SFIT SAW devices The parameters of the SFIT are listed on Table 1. Figure 4 shows the simulated frequency response of the SFIT used in this paper.

λmin of SFIT	8μm
λmax of SFIT	12.8μm
Input pairs of SFIT	30
Output pairs of SFIT	20
Aperture	700μm
Propagation distance	3326μm
Maximum tilt angle	6°
Metal ratio	0.5
Thickness of electrode	0.08μm

Table 1: Geometric parameter of the SFIT

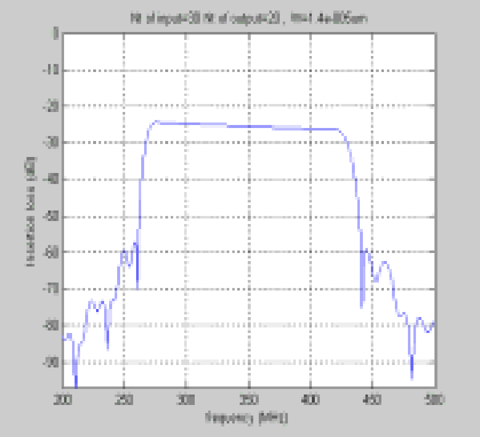

Figure 4: Frequency response of the SFIT

4 SPECTRAL ANALYSES OF SURFACE WAVES

To obtain the dispersion curves of the SAW in the layered structure, the spectral analysis of surface waves was invoked. The phase difference of two wave signals received at two different positions x_1 and x_2 is equal to the phase angle of S_{x_1,x_2} which is defined as [10].

$$S_{x_1,x_2}(f)=\frac{1}{n}\sum_{i=1}^{n}\left\{\left[R_1(f)\right]_i\cdot\left[R_2^*(f)\right]_i\right\} \qquad (5)$$

In the above equation, $R_1(f)$,$R_2(f)$ are the frequency spectrum of the wave signals received at two different positions x_1 and x_2, f is the frequency of the harmonic wave. R_2^* denotes the complex conjugate of R_2 and n is the number of times the experiments repeated. On utilizing Eqs.(4) and (5), we can obtain the dispersion relation between the phase velocity of surface wave and frequency.

5 RESULTS AND CONCLUSION

The thickness of the thin film was measured using a surface profiler as 0.6μm. Figure 5 shows the dispersion SAW phase velocity as a function of frequency for the 0.6μm thin SiO_2 film. In Figure 5, the open circles stand for the measured velocity dispersion data, and the dash line is the theoretical dispersion velocity for the 0.6μm thin SiO_2 film. The theoretical dispersion was calculated based on the density and elastic constants for bulk quartz as a density of 2200 kg/m^3 and the elastic constants as C_{11}=78.5GPa and C_{44}=31.2GPa. Mismatch between the measured and the calculated ones was found and the differences are due to the differences between the properties of a bulk sample and those of a thin film. We then, utilized an inverse algorithm based on the simplex method [11, 12] to recover the density and the two elastic constants from the measured velocity dispersion data (open circles). The inverse recovered elastic constants and density of the thin SiO_2 film were C_{11}=74.2GPa, C_{44}=26.2GPa and density=2200 kg/m^3 which are similar to the values measured by Hickernell and his coworkers[6].

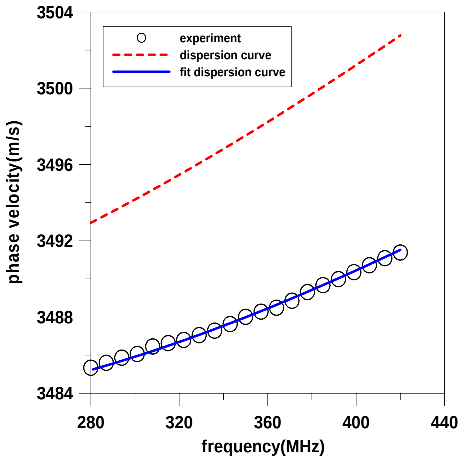

Figure 5:measured SAW velocity dispersion (open circles) for PECVD SiO_2 on $LiNbO_3$ with best fit theoretical dispersion curve (solid line)

It is worth noting that if in a fabrication process, the density and the elastic constants of the thin SiO_2 film are known, then, it is simple to evaluate inversely the thickness of the thin film using the measured dispersion of SAW and the above mentioned inverse algorithm.

In summary, we have presented a novel method using the forward solution and the measured dispersion of thin films to determine the material properties of sub-micrometer thin films. On the other hand, the thickness of thin films can be inversely determined by using an inverse algorithm when the material properties are known. It is worth noting that results of this study can be employed to design an in-situ thin film thickness monitoring SAW sensor.

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