LASER ULTRASONIC CHARACTERIZATION OF RESIDUAL STRESSES IN THIN FILMS

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ABSTRACT. In previous work, we showed that laser ultrasonics (photo-acoustics) is a promising tool for the nondestructive and non-contact characterization of thin film structures. In particular it was shown that the modulus and residual stresses in two-layer freestanding Al/Silicon Nitride films could be measured using a narrow-band laser ultrasonic technique. In this technique, a microchip laser deposits pulsed laser energy as a spatially periodic source on the structure. The resulting narrowband ultrasonic modes are monitored using a broadband Michelson interferometer. By varying the geometry of the spatially periodic source, a wide range of wavenumbers can be probed. For the thin films investigated, which were less than a micron in thickness (300-900 nm), only the two lowest order modes were generated and these in turn can be related to sheet and flexural modes in plates. In this paper we present an extension of this approach. The sensitivity of the photo-acoustic system is examined by measuring variable residual stresses. Variable residual stresses are obtained in the thin films by two methods: by varying the growth rates for silicon nitride and by varying the membrane size.

INTRODUCTION

A photoacoustic microscope was used to generate and detect narrowband guided waves in freestanding thin films. The films consist of two layers, one of aluminum and another of silicon nitride. By crossing two pulsed laser beams on the surface of a film, a spatially periodic source is created. The result is the generation of narrowband guided waves with a fixed wavenumber [1-2]. A wide region of wavenumbers can be probed by varying the geometry of the periodic source. The two lowest order Lamb waves, the symmetric, S

0

, and the antisymmetric, A

0

, modes, are generated in these films. Dispersion curves for these two modes can be obtained by testing over a wide range of wavenumbers. Using plate theory, velocity equations can be derived for the two lowest order Lamb waves[3-4]. The material properties can then be calculated using the velocity equations and dispersion curves.

Photoacoustic Microscope

A schematic of the photoacoustic microscope is shown in Figure 1. A microchip laser with a pulse length of 800 ps and pulse energy of 3.9 μJ was used as the generation laser. The beam was separated into two parallel beams with a beam spacing of d. The two
beams were then focused onto the surface of the film. The beams overlap and the result is an interference pattern in the form of a spatially periodic grating \[1-2\]. This spatially periodic source generates guided waves in the films with a fixed wave number. The wavenumber generated is a function of the angle, \(\theta\), the angle at which the two beams are crossed and the wavelength of the generation laser, \(\lambda_g\), see Equation 1.

\[
k = \frac{4\pi}{\lambda_g} \sin \left( \frac{\theta}{2} \right)
\]  
(1)

The generated guided waves are detected using a balanced Michelson interferometer. The detection laser is a CW Nd:YAG laser with a wavelength of 532 nm. The peak frequency is taken from the spectrum of the time trace and is used to calculate the phase velocity as shown in Equation 3. The phase velocity for a given wave mode is found using the wavenumber, \(k\), from the source and the peak circular frequency, \(\omega\), of the detected wave mode.

\[
v = \frac{\omega}{k}
\]  
(2)

By varying the beam spacing, \(d\), between the two generation beams, a wide range of wavenumbers can be probed. Thus, dispersion curves for the two wave modes can be obtained.

In general, either broadband or narrowband generation can be used to obtain dispersion measurements \[5-6\]. The damage threshold of the sample limits the generation power. Using a point source or line source for broadband generation limits the power for generation due to ablation of the sample. However, by using narrowband generation, higher total laser power can be used to generate guided waves on the samples. The result is a higher signal to noise ratio, because the signal to noise ratio is directly proportional to the intensity of the generation laser. Also, for broadband detection it is necessary to make measurements at a number of source to receiver distances to obtain the dispersion of the velocities \[6\]. With narrowband generation, measuring the velocity dispersion on small structures is possible because the source to receiver distance can be placed at essentially a zero distance.

![Diagram](image.png)

**FIGURE 1.** Schematic of the photoacoustic microscope.
Dispersion Curve Measurements

The photoacoustic microscope was used to obtain dispersion curve measurements of free standing thin films. Only the two lowest order Lamb waves will propagate for small values of the product of the wavenumber, k, and thickness, h. For the thin films tested, in the order of hundreds of nanometers in thickness, even at high frequencies, the k*h values are small enough that only the $A_0$ and $S_0$ modes propagate. Using plate theory, exact solutions for the velocity equations of the $A_0$ and $S_0$ modes can be found. The $S_0$ phase velocity is given by Equation 3, where the composite stiffness and density are given by Equations 4 and 5. The volume fraction, $V_k$, where h is the total thickness of the plate and $h_k$ are the layer thicknesses for the aluminum and silicon nitride films tested, is shown in Equation 6. The $S_0$ mode is nondispersive and the velocity is dependent on the composite modulus and composite density.

$$v_{s0} = \frac{\omega}{k} = \sqrt{\frac{C^*}{\rho}}$$ (3)

$$C^* = \sum_{k=1}^{n} \frac{E_k}{1 - v_k^2} V_k$$ (4)

$$\rho^* = \sum_{k=1}^{n} \rho_k V_k$$ (5)

$$V_k = h_k / h$$ (6)

The velocity equation for the $A_0$ mode depends on the composite flexural rigidity, composite density and also average residual stress. For the $A_0$ mode, the phase velocity is given by Equation 7 where $\sigma_0$ is the composite (thickness-averaged) residual stress, and $D^*$ is the normalized composite flexural rigidity that is dependent on the material properties and thickness of the layers. The $A_0$ mode is dispersive and the velocity is affected by the average residual stress in the film.

$$v_{a0} = \frac{\omega}{k} = \sqrt{\frac{D^*(kh)^2 + \sigma_0}{\rho}}$$ (7)

EXPERIMENTAL RESULTS AND DISCUSSION

Films With Varying Residual Stress

In previous work, it was shown that the modulus values obtained for the silicon nitride and aluminum were in the range of published values for these two materials [5]. The next step was to evaluate the ability of the photoacoustic system to measure varying residual stresses. Since only the effects of residual stress affect the $A_0$ mode, only the $A_0$ mode was used in these experiments. Varying residual stresses in the film were introduced by modifying the gas flow rates when depositing the silicon nitride films. In this case two flow rates were chosen. The low gas flow rate film was grown using 6 sccm for NH$_3$ and 25 sccm for SiH$_2$Cl$_2$ and the thickness of the nitride was 430 nm. The high gas flow rate film was grown using 12 sccm for NH$_3$ and 50 sccm for SiH$_2$Cl$_2$ and the thickness of the nitride was 395 nm. For both cases, the aluminum layer had a thickness of 349 nm. Square membranes of various sizes were created on one wafer so that size effects on the measurements could be investigated. Three sizes were chosen, where the lengths of one side of the square were 0.75 mm, 1 mm and 1.8 mm.
FIGURE 2. Dispersion curve for the low gas flow rate silicon nitride and aluminum film of three square sizes.

Results

Figures 2 and 3 show the dispersion curves for the low and high gas flow rate films and the three square sizes. As can be seen, the velocities are dispersive and essentially linearly varying with $(k^*h)^2$. The velocity equation for the Ao mode and a least squares fit was used to calculate the flexural rigidity and residual stress in the films. These results are shown in Table 1.

Discussion

Using a range of values published for aluminum and silicon nitride the flexural rigidity is expected to range between 8.9 to 14.1 GPa. As can be seen, the flexural rigidity values measured experimentally are in this range with the exception of the square membrane with a side of 0.75 mm and a low gas flow rate silicon nitride layer. In this case, it is suspected that generation and detection were near an edge and so edge effects
TABLE 1. Experimental results for flexural rigidity and residual stress.

<table>
<thead>
<tr>
<th>Wafer with</th>
<th>D*</th>
<th>Residual Stress</th>
</tr>
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<tbody>
<tr>
<td>Low Gas</td>
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<td></td>
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<tr>
<td>Flow Rate</td>
<td></td>
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<tr>
<td>Nitride</td>
<td></td>
<td></td>
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<tr>
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<td>15.0</td>
<td>483</td>
</tr>
<tr>
<td>1</td>
<td>11.4</td>
<td>519</td>
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<tr>
<td>0.75</td>
<td>25.1</td>
<td>364</td>
</tr>
<tr>
<td>High Gas</td>
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<tr>
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<tr>
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<tr>
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<td>352</td>
</tr>
<tr>
<td>0.75</td>
<td>14.4</td>
<td>352</td>
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could have influenced the experimental results. There is a clear variation in residual stress between the film with a low gas flow rate silicon nitride layer, with stress between 480-520 MPa, and a high gas flow rate silicon nitride layer, with a residual stress measurement between 352-363 MPa. The results for the wafer with a high gas flow rate silicon nitride layer shows very consistent measurements for the flexural rigidity for the three square membrane sizes.

CONCLUSION

The photoacoustic microscope was used to measure variation in residual stress for a two layer free standing thin film. The dispersion curve for the lowest order antisymmetric Lamb wave was obtained since only this mode is affected by the average residual stress in the film. A clear difference can be seen in residual stress by varying the gas flow rates during fabrication of the films and this variation can be measured using laser ultrasonics. Finally, the values obtained for the flexural rigidity are within the range of values obtained using a range of published values for the aluminum and silicon nitride.

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REFERENCES