Thickness Measurement of Aluminum Thin Film using Dispersion Characteristic of Surface Acoustic Wave

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Abstract—In this study, we suggest a method to measure the thickness of thin films nondestructively using the dispersion characteristics of a surface acoustic wave propagating along the thin film surface. To measure the thickness of thin films, we deposited thin films with different thicknesses with range of 200~1000 nm on a Si(100) wafer by controlling the deposition time by DC sputtering technique. The thickness of the thin films was measured using a scanning electron microscope. Subsequently, the surface wave velocity of the thin films with different thickness was measured using V(z) curve method of scanning acoustic microscopy. The correlation between the measured thickness and surface acoustic wave velocity was verified. The wave velocity of the film decreased as the film thickness increased. Consequently, film thickness can be determined by measuring the dispersion characteristics of the surface acoustic wave velocity.

Keywords-component; scanning acoustic microscope; V(z) curve; dispersion; surface wave velocity; thin film thickness

I. INTRODUCTION

In recent years, nano-structured thin film systems are often applied in industries (e.g., MEMS/NEMS device, semiconductor, display, optical coating or the like). Thin film are used for many and varied purpose to provide resistance to abrasion, erosion, corrosion, galling, tarnish, wear, radiation damage, or high temperature oxidation and to reduce friction or electrical resistance, provide lubrication, prevent sticking, and also to provide special magnetic or dielectric properties[1-4].

Particularly, aluminum thin films are widely used for optical mirrors, fiber-optic probes, thin film transistor and flat panel displays[5-8]. The physical and elastic properties of the Al thin films depend strongly on their film thickness. Film thickness significantly affects coating quality and costs. Coating thickness plays an important role in product quality, process control and cost control and it can be measured with many different methods such as atomic force microscopy, alpha-step and scanning electron microscope and so on[9-10]. However, these methods do not maintain the functionality of films after testing and the thickness of the film might be changed when cutting or eliminating layers of the system because these all are destructive method. In this study, V(z) curve method was applied to measure the thickness of the thin film using scanning acoustic microscopy nondestructively.

II. THEORY

A. V(z) curve

Figure 1 shows a schematic diagram of surface acoustic wave (SAW) propagation between the acoustic lens and the specimen via a coupling medium (e.g., distilled water). In theory, the oscillations of the received signal can be explained by the interference between the specularly reflected acoustic wave (path #1) and the surface acoustic wave (path #2). A surface acoustic wave can be generated at a liquid-solid interface if the half aperture angle of the acoustic lens is greater than the second critical angle for the surface. A surface acoustic wave can propagate along the specimen surface and radiate energy into the liquid at the critical angle. The surface acoustic wave can interfere with the specularly reflected acoustic waves at the acoustic sensor and this interference will produce alternating maxima and minima in the acoustic output signal depending on the distance between the acoustic lens and the specimen.

![Figure 1 Example of the V(z) curve](image-url)
The plot of the interference is the so-called V(z) curve[11-13]. Here, “V” represents the amplitude of the received signal and is a function of “z”, which represents the distance between the specimen and the acoustic lens. Figure 1 shows an example of the V(z) curve. The specimen is silica glass. The temperature of the coupling medium (i.e., de-ionized water) is 23. The operating frequency of the acoustic lens (Olympus; model: AL4M631) is 400 MHz. The velocity of the SAW is calculated by measuring the spacing of the minima Δz.

B. Calculation of surface wave velocity

In this study, we use the ray model to calculate the surface wave velocity illustrated in Fig. 2. The ray model is based on the ray interference theory [14-15]. According to the ray theory, when the specimen is displaced from z=0 toward the acoustic lens by z, the path #1 and #2 respectively experience the following phase change. Here, z=0 is set at the focal point of the acoustic lens and the positive z direction is away from the lens. When the specimen is at a distance z from the lens focal plane, the phase lags of δ₁₁ (for path #1) and δ₁₂ (for path #2) are expressed by:

\[
\delta_{11}(z) = -2BO \cdot k_w = -2 \cdot z \cdot k_w
\]

\[
\delta_{12}(z) = -AOC \cdot k_w + AC \cdot k_R
\]

where \( k_w \) and \( k_R \) stand for the wavenumber in the water between the lens and specimen and of the surface wave respectively. A phase change of 2\( \pi \) in relative phase difference corresponds to a dip or peak interval in V(z) curve. Using Eq. (2) and Snell’s law, it follows that:

\[
\Delta z = \delta_{12}(z) - \delta_{11}(z)
\]

\[
= 2z \left[ k_w \left( 1 - \frac{1}{\cos \theta_R} \right) + k_R \cdot \tan \theta_R \right]
\]

(2)

where \( k_w \) and \( k_R \) stand for the wavenumber in the water between the lens and specimen and of the surface wave respectively. A phase change of 2\( \pi \) in relative phase difference corresponds to a dip or peak interval in V(z) curve. Using Eq. (2) and Snell’s law, it follows that:

\[
\Delta z = \frac{v_w}{2 \cdot f \cdot (1 - \cos \theta_R)}
\]

(3)

Using Snell’s law again for the angle \( \theta_R \) in the denominator, we can rewrite Eq. (3) in the form that explicitly express the surface acoustic wave velocity \( v_R \) as a function of \( \Delta z \):

\[
v_R = \frac{v_w}{\sqrt{1 - \left( \frac{v_w}{2 \cdot f \cdot \Delta z} \right)^2}}
\]

(4)

III. EXPERIMENTAL DETAILS

Aluminum films, having thickness in the 200–1000 nm range, were deposited on silicon substrate by DC magnetron sputtering technique [10-11]. The deposition time was controlled to obtain the thin film specimens with different film thickness. The chamber pressure during sputtering was about 5 \times 10^{-6} Torr. The target used for film preparation was high-purity (99.99%) Al. The films were grown on silicon substrates with previous cleaning process. During film growth the distance substrate-source was 70 mm. The average deposition rate was 1.1 nm/sec approximately. Table 1 showed the deposition time for each specimen to obtain the expected film thickness.

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Film Thickness(nm) (expected)</th>
<th>Deposition Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>200</td>
<td>3min 2s</td>
</tr>
<tr>
<td>2</td>
<td>400</td>
<td>6min 4s</td>
</tr>
<tr>
<td>3</td>
<td>600</td>
<td>9min 5s</td>
</tr>
<tr>
<td>4</td>
<td>800</td>
<td>12min 7s</td>
</tr>
<tr>
<td>5</td>
<td>1000</td>
<td>15min 9s</td>
</tr>
</tbody>
</table>

TABLE 1 Deposition time for obtaining the expected film thickness
The film thickness was measured by scanning electron microscope. The surface wave velocity was measured by V(z) curve method of scanning acoustic microscope (SAM). Fig. 3 is a schematic diagram of the scanning acoustic microscope (Model; Olympus UH3). The SAM was operated with frequency at 400 MHz. The acoustic lens used was the model AL4M631, comprising a zinc oxide transducer (diameter 383 μm) for converting the electric signals generated by a RF tone-burst source, the sapphire buffer rod, and the spherical recessed portion of the acoustic lens. The lens has an aperture angle of 120°, and the focal distance of 577.52 μm. Deionized water was used as a coupling medium between the lens and the specimen. The acoustic wave velocity in water is the important factor in V(z) measurement, it can directly affect the accuracy of the surface acoustic wave velocity according to Eq. (4) \[18-19\]. During experiments, the water temperature can be kept at around 22.5°C so as to reduce the temperature error.

### IV. RESULTS

Aluminum films with different thickness were deposited on glass substrate in order to verify a change of the surface wave velocity depending on the film thickness.

Table 2 shows the measured film thickness using scanning electron microscope. The film thickness increased as the deposition time was increased expectably. A V(z) curve was obtained by scanning acoustic microscope for each specimen. The Δz was measured for each specimen and then the surface acoustic wave velocity was calculated by Eq. (4). A surface wave velocity was measured three times per specimen to reduce the measurement error. As mentioned above, a surface acoustic wave velocity in water was changed in accordance with water temperature. When a temperature of water the wave velocity is 1490 m/s. Table 3 shows measured surface acoustic wave velocity. The correlation between the measured thickness and surface wave velocity was verified. The surface wave velocity tends to decrease as the thickness of aluminum thin film increased as shown Fig. 4.

### V. CONCLUSION

In this study we suggest a method that can measure the thickness of thin films nondestructively using dispersion characterization of surface acoustic wave propagating the thin film surface. A surface wave velocity was measured by V(z) curve method using scanning acoustic microscope. To verify the correlation between the measured thickness and surface wave velocity.
wave velocity, the film thickness was measured using scanning electron microscope. As film thickness increased, the surface wave velocity decreased. Consequently, thin film thickness can be determined by measuring the dispersion characteristic of surface acoustic wave velocity using V(z) curve method.

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