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

Ik Keun Park,
Department of Mechanical &Automotive Engineering
Seoul National University of Science and Technology
Seoul, Korea
ikpark@seoultech.ac.kr

Tae Sung Park
Department of Mechanical Engineering
Hanyang University
Seoul, Korea
taesung78@seoultech.ac.kr

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; dipersion;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.

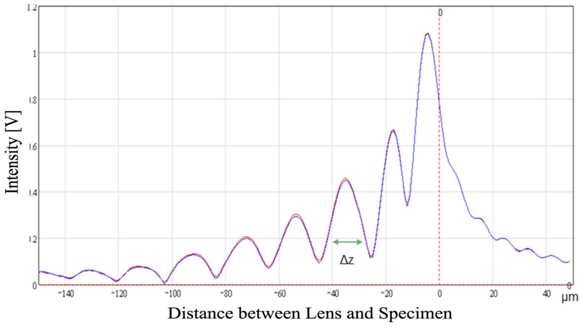

Figure 1 Example of the V(z) curve

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 velociry

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 $\delta_{\#1}$ (for path #1) and $\delta_{\#2}$ (for path #2) are expressed by:

$$\begin{aligned}\delta_{\#1}(z) &= -2\overline{BO}\cdot k_w = -2\cdot z\cdot k_w \\ \delta_{\#2}(z) &= -\overline{AOC}\cdot k_w + \overline{AC}\cdot k_R\end{aligned} \tag{1}$$

Here $\delta_{\#1}$ and $\delta_{\#2}$ are the phase changes for path #1 and path #2. The relative phase change between the two paths is given as follows:

$$\begin{aligned}\Delta z &= \delta_{\#2}(z) - \delta_{\#1}(z) \\ &= 2z\cdot\left[k_w\cdot\left(1-\frac{1}{\cos\theta_R}\right)+k_R\cdot\tan\theta_R\right]\end{aligned} \tag{2}$$

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 2π 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:

$$\Delta z = \frac{v_w}{2\cdot f\cdot(1-\cos\theta_R)} \tag{3}$$

Using Snell's law again for the angle θ_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 Δz.

$$V_R = \frac{v_w}{\sqrt{1-\left(1-\frac{v_w}{2\cdot f\cdot\Delta z}\right)^2}} \tag{4}$$

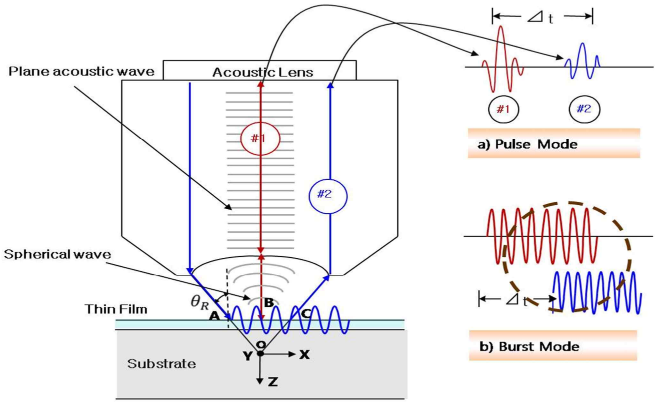

Figure 2 Schematic diagram showing the principle of the V(z) curve

where, v_w is the acoustic velocity in water and f is the working frequency. This simple ray optics theory allows quantitative measurement of the phase velocity of a surface acoustic wave from V(z) curve, and characterization of the acoustic properties of materials. By changing the distance between the lens and specimens, (changing distance z), we can get a V(z) curve. The velocity of the SAW is calculated from the spacing of the in Fig. 2 through Eq. (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 5×10^{-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 1 Deposition time for obtaining the expected film thickness

Sample Number	**Film Thickness(nm) (expected)**	***Deposition Time***
1	200	3min 2s
2	400	6min 4s
3	600	9min 5s
4	800	12min 7s
5	1000	15min 9s

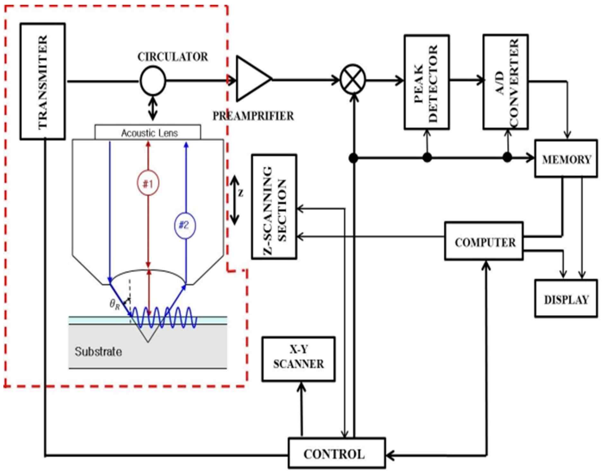

Figure 3 Schematic diagram of SAM for measuring the V(z) curve

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 ㎛) 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 ㎛. 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℃ 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 1490m/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 decreased as the thickness of aluminum thin film increased as shown Fig. 4.

TABLE 2 Measured film thickness using scanning electron microscope

Sample Number	**Film Thickness(nm) (measured)**
1	217
2	469
3	311
4	744
5	951

TABLE 3 Measured surface acoustic wave velocity

Unit :m/s

Sample Number	**P1**	**P2**	**P3**	**Mean Value**
1	3,066	3,069	3,081	3,072
2	3,044	3,077	3,077	3,066
3	3,044	3,041	3,051	3,045
4	3,009	3,016	3,044	3,023
5	3,006	3,009	3,006	3,007

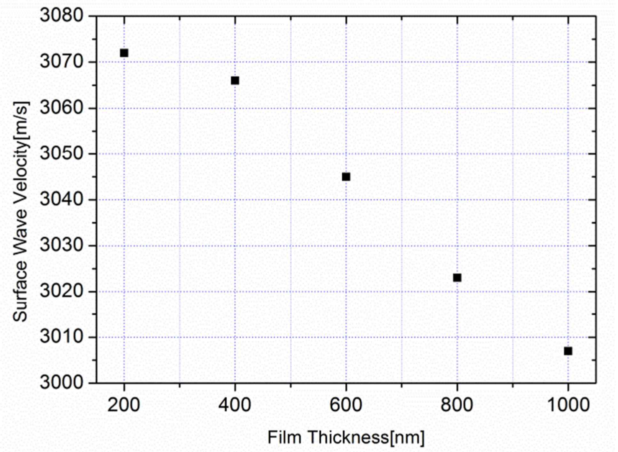

Figure 4 A change of the surface wave velocity in accordance with film thickness

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, 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.

ACKNOWLEDGMENT

This work was supported by Radiation Technology R&D program through the National Research Foundation of Korea funded by the Ministry of Science, ICT & Future Planning (NRF-2013M2A2A9043274)

REFERENCES

[1] H. S. Ju and B. R. Tittmann, "Recent ad- vances in scanning acoustic microscopy for adhesion evaluation of thin films," Journal of the Korean Society for Nondestructive Testing, Vol. 29, No. 6, pp. 534-549 (2009)

[2] C. S. Kim and I. K. Park "Review of micro/ nano nondestructive evaluation technique(I): surface and subsurface investigation," Journal of the Korean Society for Nondestructive Testing, Vol. 32, No. 2, pp. 198-209 (2012)

[3] C. S. Kim and I. K. Park "Review of micro/ nano nondestructive evaluation technique(II): measurement of acoustic properties," Journal of the Korean Society for Nondestructive Testing, Vol. 32, No. 4, pp. 418-439 (2012)

[4] V. Natarajan, "Micro and nano science and technology: naval perspective," Science Spectrum, Defence Research & Development Organization, March, pp. 237-244 (2009),

[5] K. Guenther, I. Penny, R. R. Willey, "Corrosion-resistant Front Surface Aluminum Mirror Coatings" Optical Engineering Vol. 32 pp. 547 – 552 (1997)

[6] C. W. Hollars, R. C. Dunn, "Evaluation of Thermal Evaporation Conditions Used in Coating Aluminum on Near-field Fiber-optic Probes" Review of Scientific Instruments Vol. 69, pp. 1747 – 1752, (1998)

[7] H. Takatsuji, T. Arai, "Pinholes in Al Thin Films: Their Effect on TFT Characteristics and a Taguchi Method Analysis of Their Origins", Vacuum, Vol. 59, pp. 606-613 (2000)

[8] A. T. Voutsas, Y. Hibino, R. Pethe, E. Demaray, E. "Structure Engineering for Hillock-free Pure Aluminum Sputter Deposition for Gate and Source Line Fabrication in Active-matrix Liquid Crystal Displays", Journal of Vacuum Science and Technology A 16 pp. 2668 – 2667 (1998)

[9] C. C. Wu, H. C. Change, "Opaque Estimating the thickness of hydrated ultrathin poly(o-phenylenediamine)film by atomic force microscopy", Analytica Chimica Acta 505, pp.239-246 (2004)

[10] A. Piegari and E. Masetti, "Thin Film Thickness Measurement : A Comparision of Various Techniques", Thin Solid Films, Vol, 124, pp. 249-257 (1985)

[11] C. Miyasaka. B. R. Tittnann, S. I. Tanaka, " Characterization of Stress at a Ceramic/Metal Joined Interface by the V(z) Technique of Scanning Acoustic Microscopy", Transaction of the ASEM, Vol. 124 (2002)

[12] R. D. Weglein, ''A Model for Predicting Acoustic Materials Signatures,'' Appl. Phys. Lett., Vol. 34, pp. 179–181 (1978)

[13] W. Parmon and H. L. Bertoni, "Ray Interpretation of the Material Signature in the Acoustic Microscope", Electron. Lett., Vol. 15, pp. 684–686.(1979)

[14] R. D. Weglein, "A model for predicting acoustic materials signatures," Applied Physics Letter, Vol. 34, pp. 179-181 (1978)

[15] M. Duquennoy, M. Ourak, W. M. Xu, B Nongaillard and M. Ouaftouh, "Observation of V(z) curves with multiple echoes," NDT&E International, Vol. 28, pp. 147-153, (1995)

[16] J. Kovac, H, Stock, H. Zoch, " Influence of substrate bias voltage on the properties of sputtered aluminum-scandium thin sheets," Surface Engineered Materials and Advanced Technology, vol. 2, pp. 115-119 (2012)

[17] H. H. Park, H. M. Shin, S. Y. Cha, J. W. Park, S. Y. Jeong, H. J. Pak and C. R. Cho, "Deposition-Temperature Effects on AZO Thin Films Prepared by RF Magnetron Sputtering and Their Physical Properties," The Korea Physical Society, vol. 49, pp. S584-S588 (2006)

[18] J. Du, B. R. Tittmann, H. S. Ju, "Evaluation of film adhesion to substrate by means of surface acoustic wave dipersion," Thin Solid Films, Vol. 518, pp. 4786-5795 (2010)

[19] J. Du, Toward the acvoustic evaluation o low modulus thin film structures," Doctoral Thesis, The Pennsylvania State Universiy (2008)