MATEC Web of Conferences **32**, 05006 (2015)
DOI: 10.1051/matecconf/20153205006

An application of Mueller matrix polarimetry for characterising properties of thin film with surface roughness

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Abstract. A new Mueller ellipsometry method was proposed for characterising the optical properties of thin films with rough surfaces. The validity of the proposed study is demonstrated by comparing the experimental results of the refractive index and thickness of thin film with the analytical results. Furthermore, the proposed study extracted successfully the surface roughness of thin film samples in a non contact optical manner. It provides a potential solution to replace the well-known effective approximate medium (EMA) method in dealing with the fine coarse rough surface thin film

1 Introduction

Mueller matrix polarimetry is a common method which providing a potential technique to deal with depolarization effects caused by scattering from the rough surfaces of a thin film [1-3]. However, these studies only characterized the contribution of depolarization effects within the principal Mueller matrix of sample. The present study developed a so-called decomposition model based on Mueller matrix polarimetry technique to obtain the depolarization matrix caused by scattering from surface roughness of an anisotropic thin film. The optical/physical properties (i.e., thickness, refractive indices and surface roughness) and surface roughness of isotropic thin films with either fine or coarse rough surfaces were also extracted and compared with the known value to confirm the validity of the propose approach.

2 Mueller ellipsometry method

The decomposition model for a thin film with rough surface is shown as Fig.1. As shown, thin film is modeled with two layers including $[M]_d$ and $[M]_r$ that represented for matrices of depolarization effect and reflectance, respectively when the light incident on thin film surface. Thus, the Mueller matrix of the optical model for a rough surface thin film can be expressed as

$$[M]_{\text{thinfilm}} = [M]_d [M]_r [M]_d \qquad (1)$$

For anisotropic thin films, $[M]_r$ can be easily calculated using the 4x4 matrix method [4]. The depolarization matrix $[M]_d$ cause by scattering effects from the rough surface has the form as [5]

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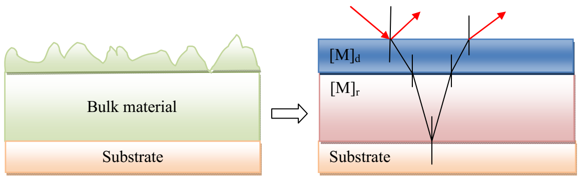

Figure 1. Decomposition model of thin film.

The so-called pure polarization matrix of the sample was obtained by multiplying both sides of Eq. (1) by $[M]_d^{-1}$ in order to eliminate the depolarization effect, can be expressed as

$$[M]_{Pure} = [M]_d^{-1}[M]_d[M]_r[M]_d[M]_r^{-1} \qquad (2)$$

The above thin film can be described by a 4x4 Mueller matrix as $S = [M]_{\text{thinfilm}} S'$, where S is the Stokes vector of the output light and S′ is the Stokes vector of the input light. For four different input lights (0^0, 45^0, 90^0 and 135^0) and two circular polarization lights (right hand (R-) and left hand (L-)) provide a sufficient number of constraints to inversely extract the depolarization matrix, refractive index and thickness of a thin film using a GA fitting technique.

3 Experimental setup and results

Figure 2 presents a schematic illustration of the experimental setup. In performing the experiments, the incident angle of the input light was fixed at 60^0, the scanning polarized angle was adjusted incrementally from 0^0 to 180^0 in steps of 15^0 by rotating the second polarizer, the R- and L-hand circular polarization lights were produced by removing the second polarizer from the experimental configuration.

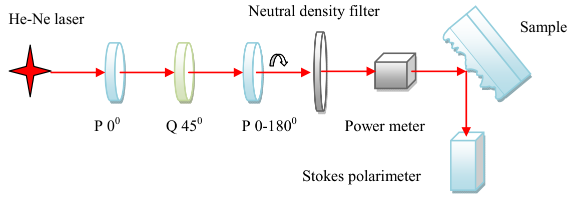

Figure 2. Experimental setup.

The experiments were performed using an HfO_2 thin film deposited on an isotropic silicon substrate. The refractive indices of HfO_2 thin film: n_o = 2.1 and n_e = 2.05; thickness of thin film: d = 215nm; and refractive index of silicon substrate: n = 3.88. Thin-film samples with two different surface roughness *Ra*=6nm and 200nm were prepared. As a result, the depolarization matrix was obtained as below.

$$[M]_{d,6nm} = \begin{bmatrix} 1.000 & 0.248 & 0.702 & 0.015 \\ 0 & 0.936 & 0 & 0 \\ 0 & 0 & 0.525 & 0 \\ 0 & 0 & 0 & 0.520 \end{bmatrix}$$

$$[M]_{d,200nm} = \begin{bmatrix} 1.000 & 0.119 & 0.706 & 0.354 \\ 0 & 0.939 & 0 & 0 \\ 0 & 0 & 0.425 & 0 \\ 0 & 0 & 0 & 0.414 \end{bmatrix}$$

The refractive indices and thickness were extracted by GA with the search space of $2.0 \leq n_e \leq 2.1$, $2.05 \leq n_0 \leq 2.15$, and $210nm \leq d \leq 220nm$, respectively. The corresponding extracted values for the sample with surface roughness Ra=6 nm are n_o=2.13, n_e=2.06 and d=212nm. The corresponding extracted values for Ra=200nm samples are n_o=2.06, n_e=2.01 and d=211nm, respectively. The results shown a good agreement exists between the extracted values of the refractive indices, thickness of the thin film and the known values. Fig. 3 compares the GA-fitted results for the six effective ellipsometric parameters (calculated as [6]) of the thin film sample with those obtained experimentally. The good agreement between the two sets of results confirms the feasibility of the proposed GA-fitting method.

For investigating the surface roughness of thin film, a combination of the proposed method and EMA method were applied. The rough surface layer was modeled as an effective layer with refractive index n_s and thickness d_s. Again, the GA was employed for extracting n_s and d_s of the rough surface layer. For Ra=200nm sample, the extracted value were n_s=1.55 and d_s=205.4 nm. For a sample with surface roughness Ra=0.6 nm, the extracted value were n_s=1.58 and d_s=0.80nm. It is found that the small deviation between the extracted value and known value is possibly caused by the error from measurement system and the imperfect of optical components itself. In general, the results are acceptable and this is the first time that the surface roughness was extracted by a non-contact optic manner.

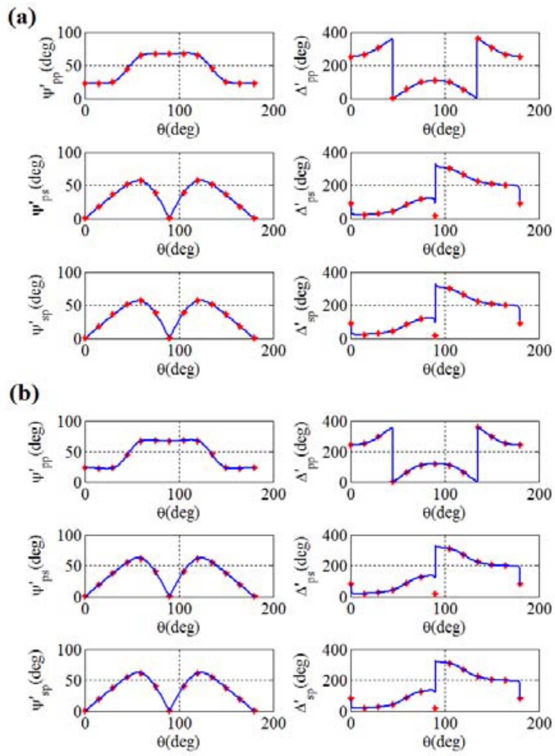

Figure 3. Experimental and GA curve-fitting results for effective ellipsometric parameters of anisotropic thin film: (a) *Ra* = 6nm and (b) *Ra*=200nm.

4 Conclusions

This study has proposed a new Mueller matrix polarimetry for inversely extracting the thickness, refractive indices of anisotropic thin films together with the depolarization matrix caused by surface roughness. In addition, the proposed approach was used to extract successfully the surface roughness of a thin-film sample in a non-contact optic manner. In general, the results confirm that the method provides an ideal approach for characterizing the optical properties of high scattering media such as biological tissues and other biomaterials.

Acknowledgement

The authors gratefully acknowledge the financial support provided to this study by the Ministry of Science and Technology under Grant No. 102-2221-E-006-043-MY2.

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