

# An auto-focusing method for imaging ellipsometry system

Y. H. Meng<sup>\*,1,2</sup>, S. Chen<sup>1,2</sup>, and G. Jin<sup>\*,1</sup>

<sup>1</sup> Institute of Mechanics, Chinese Academy of Sciences, Beijing 100080, P.R. China

<sup>2</sup> Graduate School of Chinese Academy of Sciences, Beijing 100039, P.R.China

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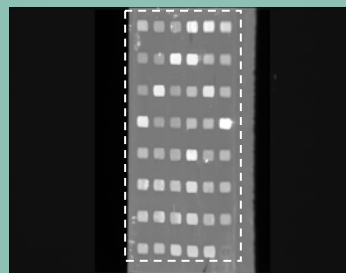
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\* Corresponding author: e-mail gajin@imech.ac.cn, Phone: +86 10 8254 4138, Fax: +86 10 8254 4138

\*\* e-mail yhong@imech.ac.cn, Phone: +86 10 8254 4137, Fax: +86 10 8254 4139

An auto-focusing method based on the image brightness gradient sharpness function is presented for imaging ellipsometry system, in which the image plane of the thin-film specimen is not perpendicular to the optical axis. The clear image of a specimen with large area is obtained by moving the imaging sensor in optical axis direction and around its sensitive surface centre successively. The experimental results demonstrate its feasibility.



A tested specimen of multi-cell protein pattern.

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**1 Introduction** Imaging ellipsometry (IE) system has been employed for characterization of micro-structure and physical properties of multi-layered thin film pattern on a large area [1-3]. As a high sensitivity imaging technique, the IE system requires basically a proper focusing method to get the clear image of specimen with a large area clearly for quantitative measurement.

As a substitution of the manual focusing method which is time-consuming, imprecise and inconsistent, the auto-focusing method has been widely used in modern optical instruments such as cameras and microscopes. By now, there were several approach available, however most of them were performed only in the optical axis direction by moving the image lens or the imaging detector for adjustment of the object distance or image distance. It is unqualified for the IE system because the ideal image of the thin film specimen is planar and has a large oblique angle to the optical axis.

In order to solve this problem, an auto-focusing method based on image brightness gradient sharpness function is presented, which combines the focusing in the optical axis and the angle-tilted focusing methods by mov-

ing and rotating the imaging sensor successively. The auto-focusing method can make the planar image of a specimen clear in the entire area of view and no additional part is needed.

## 2 Theory

From the view of optical imaging, the IE system has the following features: (i) The thin film pattern specimen can be regarded as a planner object because the thickness and area of the thin film are in the order of micron and square millimeter, respectively; (ii) The specimen surface is oblique to the imaging optical axis; (iii) The light reflected from the specimen surface gets into the imaging detector directly. Therefore, the ideal image of a specimen is a planar surface oblique to the optical axis [4].

### 2.1 Geometrical image

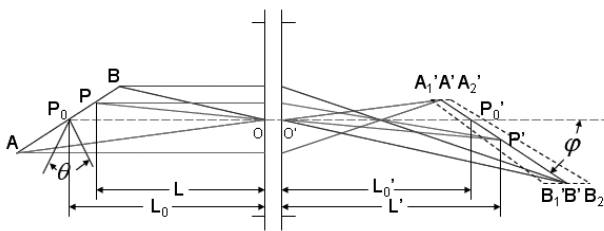
Figure 1 shows the schematic diagram of tilted imaging of the IE system. The specimen  $AP_0PB$  has an oblique angle  $90^\circ - \theta$  with respect to the optical axis, where  $\theta$  is the angle of incidence. It intersects the optical axis at point  $P_0$ , and its conjugative image is  $A'P_0'B'$ . The optical magnifica-

tion of  $P_0$  is

$$\beta_0 = \frac{f'}{L_0 - f'} \quad (1)$$

where  $f'$  is the focal length of the imaging lens and  $L_0$  is the object distance of point  $P_0$ . It is readily to get the oblique angle of the image  $A'P_0'B'$  with respect to the optical axis

$$\varphi = \arctan \frac{1}{\beta_0 \tan \theta} \quad (2)$$



**Figure 1** Schematic diagram of tilted imaging of IE system.

In a practical IE system, the sensitive surface of the optoelectronic imaging sensor such as a charged-coupled-device (CCD) is generally made up of millions of pixels. The pixel size, which is in the order of several microns, is one of the most important limited factors of the lateral resolution of the system. The other factors are the diffraction limit of the optical system and the oblique incidence, etc.

It is well-known that a focusing allowance region  $A_1'B_1'B_2'A_2'$  is formed, in which the detected image has the same lateral resolution and image definition. The front focal plane  $A_1'B_1'$  and back focal plane  $A_2'B_2'$  can be expressed as

$$y_1' = \frac{f'(1 + \beta_0) - \frac{D}{D-h} L_1'}{\beta_0 \tan \theta} \quad (3)$$

$$y_2' = \frac{f'(1 + \beta_0) - \frac{D}{D+h} L_2'}{\beta_0 \tan \theta} \quad (4)$$

where  $h$  is the single pixel size of the imaging sensor,  $D$  is the aperture of the imaging lens,  $y_1'$  and  $y_2'$  are the image heights, and  $L_1'$  and  $L_2'$  are the corresponding image distances, respectively. In order to get a clear image over the entire area of view, the sensitive area of the imaging sensor should be located in the region.

## 2.2 Image definition function

In order to evaluate if the image is in the depth-of-focus, the image definition function based on brightness gradient sharpness calculation is used. It has a unique maximum value obtained when the sensitive surface of the imaging sensor is set on the focusing allowance region.

The Laplacian function, the Robert function and the Sobel function were used widely [5]. The Laplacian function takes the form

$$FM_{Lap} = \sum_x \sum_y [\nabla^2 g(x, y)]^2 \quad (5)$$

where

$$\nabla^2 g(x, y) = 4g(x, y) - g(x, y+1) - g(x, y-1) - g(x+1, y) - g(x-1, y) \quad (6)$$

The Robert function and the Sobel function can be expressed as

$$FM_{grad} = \sum_x \sum_y [\nabla g(x, y)]^2 = \sum_x \sum_y (Gx^2 + Gy^2) \quad (7)$$

where

$$Gx = g(x, y) - g(x+1, y+1), Gy = g(x+1, y) - g(x, y+1) \quad (8)$$

for the Robert function, and

$$\begin{aligned} Gx &= g(x-1, y+1) + g(x+1, y+1) - g(x-1, y-1) \\ &\quad - g(x+1, y-1) + 2g(x, y+1) - 2g(x, y-1) \\ Gy &= g(x+1, y-1) + g(x+1, y+1) - g(x-1, y-1) \\ &\quad - g(x-1, y+1) + 2g(x+1, y) - 2g(x-1, y) \end{aligned} \quad (9)$$

for the Sobel function, where  $g(x, y)$  represents the light intensity of the point  $(x, y)$ .

In an aberration and distortion limited IE system, the value of the image definition function is affected by some factors including random noise, brightness and contrast, etc.

## 2.3 Auto-focusing method

The auto-focusing method based on the image definition function is used widely in modern instruments due to its simple structure and easy operation. The best position of the imaging sensor is at the position where the definition function obtains the maximum value.

According to the previous analysis, the imaging system carries out focusing by moving the imaging sensor in optical axis and rotating its sensitive area successively as shown in Fig. 2 to image the large area specimen clearly over the entire area of view.

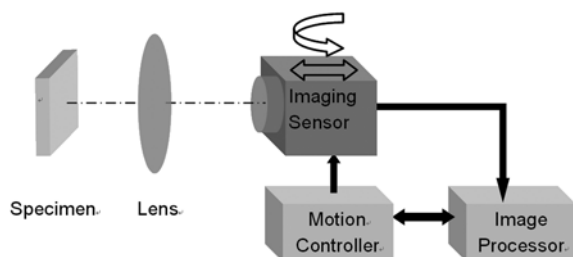
The auto-focusing method consists of three steps as follow.

(i) Preparation: The imaging sensor is driven by the controller to the ideal geometric position  $A'P_0'B'$ , then an area of interest in the image is selected for the calculation of definition.

(ii) Auto-focusing in optical axis [6, 7]: The imaging sensor is moved step by step within the given distance range near the ideal position about 10~20 times of the cur-

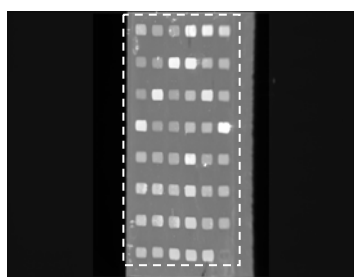
rent focal depth. At each sampling position image is captured for the calculation of the image definition function values. And the serial values are fitted with polynomial function for searching the maximum point which represents the best image definition and its responding position at optical axis is the best position. Finally, the imaging sensor is moved to the best position along optical axis.

(iii) Auto-focusing in tilted angle direction [8]. The imaging sensor is rotated step by step within the given angle range near the ideal position about  $10 \sim 20$  times of the current error allowance angle. The following steps are similar to (ii) including image capture, calculation of the image definition function and best angle position searching. Finally the imaging sensor is rotated to the best angle position.



**Figure 2** Schematic diagram of auto-focusing system based on image definition function, which combines the focusing in optical axis with the angle-tilted focusing method together by moving and rotating imaging sensor successively.

**3 Experimental** Here a multi-cell protein pattern prepared on Si substrate with a natural  $\text{SiO}_2$  thin film [9] is shown in Fig. 3. The thickness of protein is lower than 10 nm. The specimen with size of 10.5 mm (H) x 12.5 mm (V) consists of 6 (H) x 8 (V) protein cells.



**Figure 3** A tested specimen of multi-cell protein pattern, the dashed line indicates the area of interest.

A home-made automatic imaging ellipsometer [10] is used to demonstrate the auto-focusing method. The wavelength of probe beam is 633 nm. The angle of incidence is set at  $75^\circ$  close to the quasi-Brewster's angle of silicon substrate in order to improve the image contrast. The sensitive area size of CCD camera (SONY XC-30CE) is 6.0 mm x 4.96 mm. Each pixel is  $6.25 \mu\text{m}$  (H) x  $6.5 \mu\text{m}$  (V) which defines the maximum lateral resolution. The video

signal of the detected image is transferred to an A/D converter (Matrox Meteor-II) inserted in computer can form a digital image in 8 bit greyscale format.

The professional software was used to carry out the motion control, image acquisition, and the calculation of image definition function value on the area of interest.

For control purpose, a motion card (Galil PDMC9542) inserted in computer is used to provide the motion signal and receive the feedback of the position. The CCD camera is fixed on a platform which can move the CCD camera in the optical axis direction driven by a precision ball screw and rotate the sensitive area around its centre line driven by precision gear-worm, respectively. Both of the two mechanical parts are powered by 2 phase step-motors. In the present setup, the minimum distance step and angle step of CCD camera is  $1 \mu\text{m}$  and  $0.001^\circ$ , respectively.

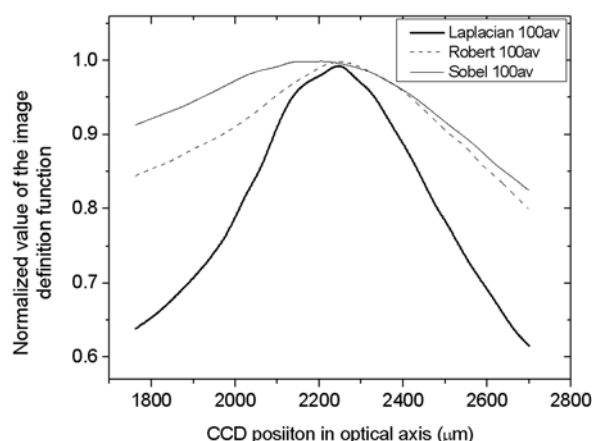
The speed of auto-focusing depends on the mechanical scanning speed, the best position searching speed and the image capturing speed, etc. In order to improve the speed, the mechanical scanning speed is set at 2 mm/s for CCD moving and  $2^\circ/\text{s}$  for CCD rotating. During the searching process, the moving and rotating step is set at  $27.6 \mu\text{m}$  and  $0.76^\circ$ , which is two times of the focal depth in the point  $P_0$  and error allowance angle. In order to improve the accuracy, half step is used to move the CCD camera to the best position. The image capturing speed is about 10 frames / s.

A proper image definition function should have high-good performance in sensitivity, therefore the Laplacian function, the Robert function and the Sobel function are compared. A multi-image averaging method is used to improve the sensitivity of the image definition by reducing the random noise.

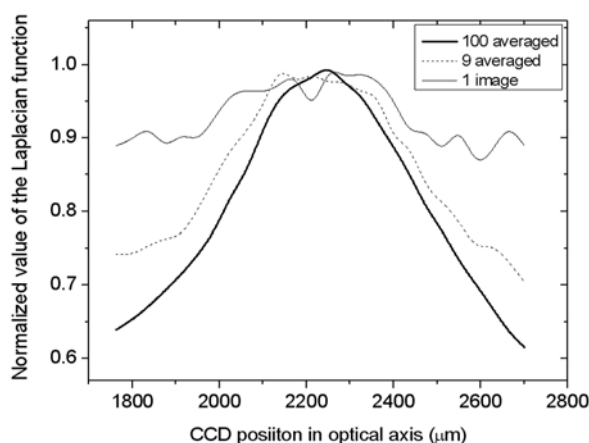
**4 Results and discussion** Figure 4 gives the normalized experimental data of three image definition functions of the Laplacian function, the Robert function and the Sobel function during focusing in the optical axis direction. 100 image averaging method was used during image grabbing process. It can be seen that there is a unique maximum value in each curve and that the peak points of each curve are almost at the same position, the value in both side of best position decreases. The Laplacian function has biggest sensitivity and is adopted as the image definition function for the system.

In order to evaluate the sensitivity of random error to the image definition function, Fig. 5 gives the normalized experiment image definition value of the Laplacian function with or without multi-image averaging. It can be seen that the sensitivity and smoothness of the function depends heavily on the random error, which can be decreased by multi-images averaging.

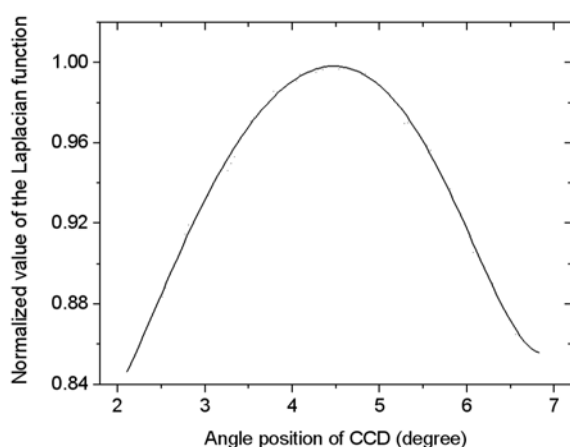
Figure 6 shows the normalized experiment data during the focusing in angle tilted direction. It can be concluded that the Laplacian function is suitable for this step as well.



**Figure 4** The normalized experiment curves of Robert function, Sobel function and Laplacian function for focusing in optical axis direction.



**Figure 5** Normalized experiment curves of the Laplacian function to (a) 1 image; (b) 9 images averaged; (c) 100 images averaged.



**Figure 6** Normalized experiment curve of the Laplacian function in angle-tilted focusing.

**5 Conclusion** An auto-focusing method based on image brightness gradient sharpness function is presented for an imaging ellipsometry system, which can obtain the best conjugative planar image of a specimen with large area by combining the focusing in optical axis and angle-tilted focusing. Experimental results demonstrate the feasibility of the auto-focusing method. The Laplacian function is chosen as the image brightness gradient sharpness function due to its high sensitivity and unique peak. The multi-image averaging method is employed to decrease the random noise to improve the sensitivity. The auto-focusing method can be used to solve the depth-of-focus problem. It can be used also in other optical systems such as the imaging surface plasma resonance system where the image is planar and oblique to the optical axis.

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