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薄膜機械特性及殘留應力之反算偵測(1/3)

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計畫主持人：吳恩柏

計畫參與人員：楊政達　邵清安

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行政院國科會專題研究計劃

薄膜機械特性及殘留應力之反算偵測 （1/3）

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摘要

薄膜特有的僅僅微米等級的厚度可能導致其行為迥異於塊材，因此以非破壞的方式測定薄膜的楊式模數、熱膨脹係數、蒲松比以及其厚度等，一直是個困難但卻極重要的問題。在本報告中，成功地展示了一次同時測定此四個參數的能力。這新穎的方法包含以數位式相移反射疊紋法的技術，記錄降溫狀態下晶圓翹曲值的斜率。當中的實驗使用 6 英吋的矽晶圓鍍上厚度為 1 微米的鋁。並以數值方式使用傳統三維有限元素法建立量得資料與其機械性質間的摺積關係，最佳化求解則使用了遺傳演算法。

關鍵字：薄膜、反算、反射式疊紋法

ABSTRACT

Nondestructive determination of Young’s modulus, coefficient of thermal expansion, Poisson ratio, and thickness of a thin film has long been a difficult but important issue as the film of micrometer order thick might behave differently from that in the bulk state. In this report, we have successfully demonstrated the capability of determining all these four parameters at one time. This novel method includes use of the digital phase-shifting reflection moiré (DPRM) technique to record the slope of wafer warpage under temperature drop condition. In the experiment, 1-um thick aluminum was sputtered on a 6-in silicon wafer. The convolution relationship between the measured data and the mechanical properties was constructed numerically using the conventional 3D finite element code. The genetic algorithm (GA) was adopted as the searching tool for search of the optimal mechanical properties of the film.

Key Words: Thin film properties, inverse method, reflection moiré.

INTRODUCTION

Measurement of mechanical properties of a thin film has long been an important but difficult problem as the film coated on a substrate is on or less than micrometer order depending strongly on the growth process, thickness, and the exposed environment. In early days, uni-axial tensile test was performed to directly measure the Young's modulus [1,2]. This method, however, is subjected to uncertainties, such as creep, and difficulties in the applying the load, measuring the elongation, etc. X-ray diffraction is another tool to record the Young's modulus and Poisson ratio of thin films [3,4], but the difficulty arises from the determination of the undeformed configuration of the thin film. Other methods, such as using the nano indentor instrument are also popular [5]. However, this is a destructive method that always induces plastic deformation.

In this study, we developed a digital phase-shift reflection moiré (DPRM) method to measure the slope change of 1-um thick aluminum film coated on a 6-inch wafer. Use of reflection moiré was because both the film and the wafer are mirror-like. The wafer itself was 677 um thick. Introducing the phase shifting method was mainly to enhance the spatial resolution from 10^{-4} rad/fringe to 10^{-6} rad/pixel. This enhancement, along with the already sensitive slope measurement, made it possible to record the warpage of the film/wafer structure when the temperature dropped from slightly above 100℃ to the room temperature. Finite element analyses using ANSYS were then performed. The genetic algorithm (GA) was adopted as the search tool to obtain the optimal mechanical properties using an objective function.

EXPERIMENTAL PROCEDURE

In order to use the inverse method to determine the mechanical properties of the thin film coated on the surface of the wafer, the deformation of the wafer subjected to any loading needs to be measured. In this study, the thermal loading is applied by dropping down the temperature on the wafer. Then, a digital phase-shifting reflection moiré (DPRM) method was developed to measure the slope of the mirror-like wafer when it cooled down to room temperature. Use of DPRM aimed at enhancing the resolution to the order of 10^{-6} rad/pixel by adopting the phase shifting algorithms. The experimental set up is shown in Figure 1. When a parallel white light passes through the grating and the beam splitter, it hits the object to be measured. As the light reflects from the object, it reaches the beam splitter again and reflects to reach the CCD. In addition, in order to measure the slope change on a two-dimensional manner, the cross grating was employed throughout this study.

In this study, we use the five-step phase shifting method. Each step shift is ð/2:

$$\cdot\,(x,y)=\frac{\bar{P}}{2\bar{L}}\left\{\left[\tan^{-1}\left(\frac{2(I_4-I_2)}{2I_3-I_1-I_5}\right)+\circledR\right]/(2\circledR)\right\} \quad (1)$$

where $I_1 \sim I_5$ are the fringe intensities of the picture taken by the CCD camera after each $\pi/2$ phase shift, $\cdot\,(x,y)$ is the discontinuous slope distribution. Each fringe was obtained by nonlinear interpolation. In order to reconstruct the phase map after the filtering process, the fast Fourier transform (FFT) method was used. The periodic change of the phase was expressed by the Poisson equation with Newmann boundary condition. This equation was then solved numerically. In order to filter out the high frequency noise and the DC background, the band-passed filter is set to be 11% larger two times the signal frequencies in FFT analysis.

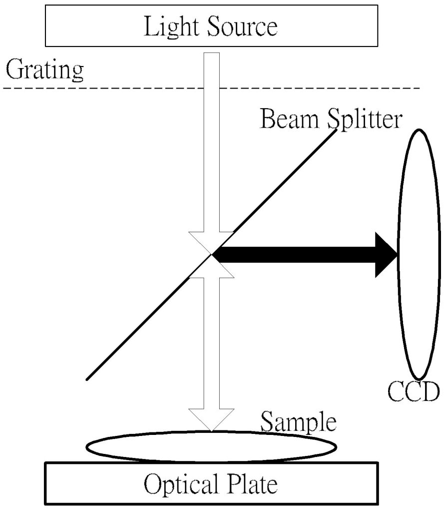


Figure 1 Setup schematic for the relative reflection digital-moiré method

FORWARD AND INVERSE ANALYSIS

In the forward analysis, ANSYS was adopted to calculate the deformation of the film/wafer composite structure under thermal loading. Since the film on the wafer was of the order of 1 um and a typical 6-inch thick wafer is 677 um, the composite element, Shell99 in ANSYS, was adopted. This composite element allows vertical integration of the strain field inside an element. Thus, it is considered to be an ideal element for this study. On the other hand, another 3D element, Solid73 in ANSYS, was also adopted to benchmark the result obtained in this study.

The inverse analysis was then employed to extract the mechanical properties from the relationship between the response of the film/wafer composite structure and the thermal loading. The genetic algorithm (GA) was adopted as the searching tool. Four important mechanical constants, i.e., Young’s modulus, coefficient of thermal expansion, Poisson ratio, and the thickness of the film were to determine. In the beginning of the search, these four mechanical properties were randomly generated. Subsequently, in each iteration a new slope based on the updated input of these four parameters were calculated. The ultimate goal is to reduce the value of the objective function:

$$fit = -\sum_{i=1}^{N}\left[\left(\text{¤}_{xi}^{cal} - \text{¤}_{xi}^{\exp}\right)^2 + \left(\text{¤}_{yi}^{cal} - \text{¤}_{yi}^{\exp}\right)^2\right] \qquad (2)$$

where ¤_{xi}^{cal} and ¤_{yi}^{cal} are the calculated slope values in each iteration using the searched material properties, $\text{¤}_{xi}^{\exp}$ and $\text{¤}_{yi}^{\exp}$ are the measured slope distributions, and N is the number of the measured data. Use of the generic algorithm is to assure convergence of the data to a globally minimum. Detailed description of the inverse method can be referred to [6,7]

RESULTS AND DISCUSSION

1. Verification of the developed method.

In order to verify the developed method, an experiment using a composite plate-like structure subjected to concentrated loading was conducted. The composite structure was composed of a mirror glued carefully on the central portion of an aluminum plate using epoxy. The mirror was 141.32 mm in length, 49.35 mm in width, and 1.90mm in thickness. The square aluminum plate was 142.38 mm wide and 1.01 mm thick. The plate was simply supported as shown in the two parallel arrows in Figure 2. A concentrated load of 2.01 kg was applied at the center of the mirror. The developed DPRM was employed to measure the slope of the plate relative to its original configuration. The measurement region of DPRM is 21.4 mm by 14.8 mm, as shown in the darken region of Figure 2, and the origin of the coordinate was set at the center of the plate. The pixel number in this region was 572 by 396. The grating pitch and the distance between the object and the grating were 200 um and 660 mm, respectively. ANSYS 8-node solid element (Solid73) was used to construct a 1/4 finite element model and performed the forward analysis.

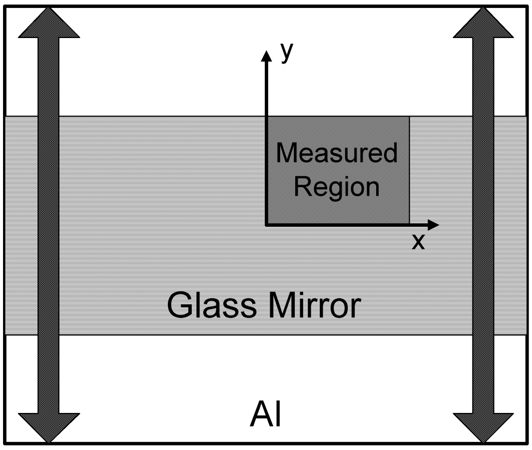
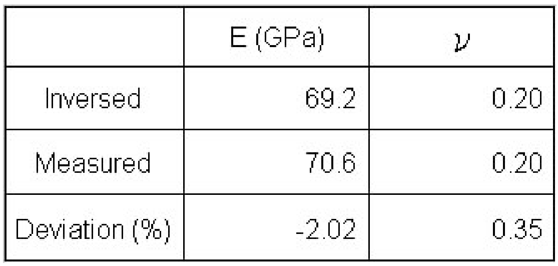


Figure 2 Schematic of the experimental setup for verification run using a mirror-aluminum composite plate structure

The ultrasonic method was used to measure the Young's modulus and Poisson ratio of the glass and the aluminum. These Young's modulus (*E*) and Poisson ratio(í) for of the glass and the aluminum are 70.64GPa and .20 and 71.4GPa and .34, respectively. In this example, the Young's modulus and the Poisson ratio for the glass were assumed to be unknowns and the developed search algorithm using GA was employed to determine these properties using the measured slope and the finite element analysis results. The result is listed in Table 1. Since the deviation between the measured and the determined materials is insignificant, the developed method is considered to be workable.



	E (GPa)	ν
Inversed	69.2	0.20
Measured	70.6	0.20
Deviation (%)	-2.02	0.35

Table 1 Measured and determined Young's modulus and Poisson ratio for the glass in the glass/aluminum structure

2. Temperature Uniformity within Wafer

The schematic of the experimental setup to measure the slope change of a wafer coated by thin metal layer is illustrated in Figure 3. In order to avoid the turbulence inside the oven that causes drift of the moiré fringe, the measurement was done outside the oven. One thermal couple, mounted underneath the wafer, was used to record the oven temperature when the wafer was heated. Once the temperature reached to a preset value, the wafer was taken out of the oven and mounted on a three-post support, in which the tip of each post was attached with a thermal couple to measure the temperature change during the cooling down process. The reflection moiré apparatus was then used to measure the slope change of the wafer during its cooling down process.

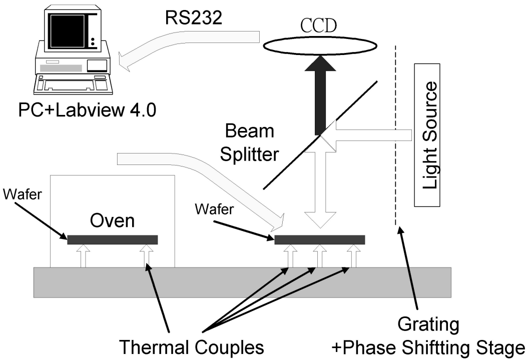


Figure 3 Schematic of the experimental setup for slope measurement of a wafer using the developed DPRM method

Finite element analysis using ANSYS Plane77 element was performed to check whether there exists any thermal gradient within the wafer during the cooling process. To align this verification to the actual experimental case, the oven, with the 6-inch wafer inside, was heated to 156℃. When the wafer was taken out and mounted on the three posts, the temperature was recorded to be 137.1℃ using the same thermal couple mounted on the wafer. After 18 seconds, the temperature on the wafer was recorded to be 78.1℃. The input data for the finite element model are the thickness (*h*), thermal conductivity (*k*), specific heat *c*, and density. For the silicon wafer, these data are 655.5 um, 138.5 W/mK, 729 J/KgK, and 2340 kg/m$^{3.}$ For the copper film used in this verification run, they were 4.5 um, 397.0 W/mK, 386. J/KgK, and 8960. kg/m^3, respectively. It is found that the thermal gradient along the thickness direction of the wafer became negligible after 18 seconds. As a result, in the subsequent experiment the warpage slope was always measured at least 18 seconds after the wafer was taken out of the oven to avoid any temperature gradient effect..

CONCLUSION

A digital phase-shifting reflection moiré (DPRM) method has been developed to measure the slope change of mirror-like structure. The resolution is up to 10^{-6}rad/pixel when the phase shifting method was employed. The cross grating was employed to record slopes in both x-and y-directions. A band-passed filter whose frequency window was approximately 11% wider than two times the fringe frequency was considered to be the optimal filter. The DPRM was then successfully adopted to measure the slope change of a wafer when it was cooled from the elevated temperature. Warpage of the wafer was due to mismatch of the mechanical properties between the thin film and the silicon wafer. An inverse method has been developed to determine these mechanical properties of the thin film, including the Young's modulus, coefficient of thermal expansion, Poisson ratio, and thickness. The Green function relationship between the mechanical properties and the slope change of the wafer was constructed using ANSYS. The genetic algorithm (GA) was adopted as the searching tool for the optimal mechanical properties of the thin film.

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