Fast, precise, tomographic measurements of thin films

Young-Sik Ghim and Seung-Woo Kim

Citation: Appl. Phys. Lett. **91**, 091903 (2007); doi: 10.1063/1.2776015
View online: http://dx.doi.org/10.1063/1.2776015
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v91/i9
Published by the American Institute of Physics.

Fast, precise, tomographic measurements of thin films

Young-Sik Ghim and Seung-Woo Kim[a)]
Billionth Uncertainty Precision Engineering Group, Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, Science Town, Daejeon 305-701, South Korea

(Received 6 June 2007; accepted 4 August 2007; published online 27 August 2007)

The authors describe a nondestructive measurement method that enables them to obtain the cross-sectional thickness profile of thin-film layers fast with a single operation of measurement. The method is based on spectrally resolved white-light interferometry, being capable of reconstructing the tomographic height map of thin films with depth resolutions in the nanometer range. In terms of the measuring speed and resolution, the proposed method is well suited for the in-line high-speed inspection of microelectronics devices produced in large quantities particularly in the semiconductors and flat panel displays industries. © *2007 American Institute of Physics*.
[DOI: 10.1063/1.2776015]

Thin films are widely used for various purposes and precise measurements of film thickness especially in a nondestructive way are crucial to ensure the intended functions of thin films. Instruments based on either ellipsometry[1,2] or reflectometry[3,4] have long been available for film thickness metrology, but they are basically capable of measuring a single point at a time. The reason is that a large amount of data needs to be collected at multiple wavelengths and/or multiple incident angles. Nowadays, the measurement speed turns out to be an important issue in meeting the industrial demand on large-volume inspection of microelectronics products. Besides, the measurement resolution in both the lateral and depth directions needs to be enhanced drastically as the product size under inspection continuously reduces with ever-increasing package density. A good example is the SiO_2 film deposited on a patterned wafer, the thickness profile of which needs to be precisely controlled by means of the chemical-mechanical-polishing process to fit within a required level of planarity.[5,6]

Recently, a different approach based on spectrally resolved interferometry was newly introduced, which enables one to obtain three-dimensional (3D) film-thickness profiles directly with a single measurement using a standard scheme of white-light scanning interferometry.[7] The idea of using spectrally resolved interferometry for 3D film metrology was later further enhanced by incorporating the concept of dispersive interferometry[8,9] but also phase-shifting technique[10] to improve the measuring speed along with high immunity to the external vibration encountered during measurement. However, a common problem with these new techniques is the severe loss of measurement accuracy for very thin films of less than 0.1 μm thickness. The reason is that only the interferometric phase information is exploited in the process of determining the film thickness, which is found less reliable as the film thickness reduces below a certain threshod limit.

In this letter, we describe an extended scheme of spectrally resolved white-light interferometry that allows one to monitor not only the interferometric phase but also the reflectance of the thin-film specimen at the same time. The underlying intention is to incorporate the principle of spectroscopic reflectometry into the Fourier-based dispersive method of white-light interferometry in order to improve the measuring accuracy. This compound approach leads to a complete 3D tomographical reconstruction of a thin-film layer in which the film thickness is determined from the spectrally resolved reflectance, while the top surface profile of the film is obtained by analyzing the interferometric phase variation with wavelength. A notable feature of this method, in comparison with existing relevant techniques,[7–10] is that the minimum measurable film thickness can be reduced far below 0.1 μm, practically down to a few nanometers, which is enough to satisfy most stringent industrial demands on thin-film metrology.

Figure 1 shows the schematic of the white-light interferometer configured in this investigation. It is basically of Michelson type with two arms; one is to generate the reference wave from a flat mirror and the other to produce the measurement wave reflecting from the specimen. At a point (x,y) on the specimen, the surface topography is characterized by two parameters $h(x,y)$ and $d(x,y)$; $h(x,y)$ represents the top surface height deviated from the reference flat, and $d(x,y)$ is the thickness of the film layer. Two identical objectives are inserted, one to each arm, to adjust the lateral measuring magnification. The light source is a tungsten halogen

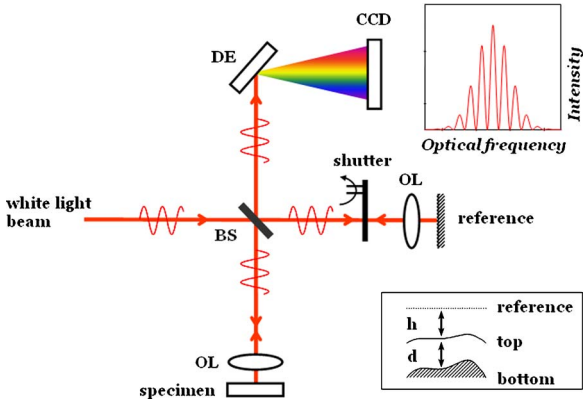

FIG. 1. (Color online) Optical configuration of spectrally resolved white-light interferometry. BS: beam splitter, DE: dispersive element, CCD: charge coupled device, and OL: objective lens. The upper right inset shows the spectral density monitored. The lower inset depicts the two morphological parameters; h is the top surface height and d the film thickness.

[a)]Electronic mail: swk@kaist.ac.kr

lamp, emitting a wide spectrum of white light spanning 420–780 nm in wavelength. The reference arm is switched on and off by means of a mechanical shutter while the interference between the reference and measurement waves is monitored using a spectrometer comprised of a diffraction line grating and a two-dimensional (2D) photodetector array. The spectrometer accepts only the central line of the interference beam through a horizontal line slit, dispersing it over the vertical dimension of the 2D photodetector array. This scheme allows a 2D tomographical measurement of a line at a time, and a complete 3D measurement is accomplished by scanning the specimen in the lateral direction sequentially using a microactuated stage.

The spectrally resolved output of the spectrometer installed in the interferometer of Fig. 1 provides the spectral density of interference intensity, which is expressed as $G(h,d;k)=G_0(k)+G_1(k)\cos\Phi(h,d;k)$ with $G_0(k)$ and $G_1(k)$ being the mean and visibility function, respectively. Both $G_0(k)$ and $G_1(k)$ are predominately affected by not only the spectral density of the white-light source itself but also the reflectance of the specimen. On the other hand, the phase $\Phi(h,d;k)$ is related to the optical path variation pertaining to the surface parameters: the top surface height h and film thickness d. Fortunately, the dependence of the phase $\Phi(h,d;k)$ upon h and d can be separated such that $\Phi(h,d;k)=2kh+\Psi(d;k)$; the first term $2kh$ is in direct proportion only to the top surface height h, and the second term $\Psi(d;k)$ relates to only the film thickness d.

The whole measurement procedure consists of two distinct steps being performed in sequence; first by blocking the reference arm by activating the shutter, and second by deactivating the shutter to allow the reference wave to interfere with the measurement wave from the specimen. When the shutter is on, the spectrometer receives only the measurement wave, the complex amplitude of which is generally given in the form of multireflection as[1,3]

$$R(d;k)=\frac{r_{01}+r_{12}\exp(-j2kNd\cos\theta)}{1+r_{01}r_{12}\exp(-j2kNd\cos\theta)}. \tag{1}$$

Note that r_{01} and r_{12} are the Fresnel reflection coefficients of the top and bottom boundaries of a film layer, respectively, θ the incident angle, and N the complex refractive index of the film layer. The spectral reflectance of the specimen is given by $\Re(d;k)=|R(d;k)|^2$, and the spectrally resolved interferometric phase is calculated as $\Psi(d;k)=\tan^{-1}[\mathrm{Im}\{R(d;k)\}/\mathrm{Re}\{R(d;k)\}]$.

The spectral density output from the spectrometer does not precisely represent the reflectance $\Re(d;k)$, since it is affected by many other factors such as the spectral transmittance of all the optical components comprising the interferometer setup as well as the spectral sensitivity of the photodetector array. It is therefore necessary to calibrate the spectrometer output using a reference specimen. For the purpose, a bare crystalline silicon wafer with no film coated on was selected as the standard specimen. In the first place, the spectral reflectance $\Re(0;k)_{\mathrm{ref}}$ of the standard specimen is precisely calculated analytically using Eq. (1) along with the relevant optical constants of crystalline silicon that are well known. Then the spectral density $G(k)_{\mathrm{ref}}$ of the reference specimen is actually measured using the interferometer. Now, for a given specimen of unknown film thickness d, its spectral reflectance $\Re(k)_{\mathrm{sam}}$ is calibrated using the spectral density $G(k)_{\mathrm{sam}}$ measured from the interferometer, following the relation of

$$\Re(k)_{\mathrm{sam}}=\frac{G(k)_{\mathrm{sam}}}{G(k)_{\mathrm{ref}}}\Re(0;k)_{\mathrm{ref}}. \tag{2}$$

Once the spectral reflectance $\Re(k)_{\mathrm{sam}}$ is obtained, the film thickness d is found by fitting the analytical model of $\Re(d;k)$ based on Eq. (1) into the measured data of $\Re(k)_{\mathrm{sam}}$ so as to minimize the total sum of squared errors of

$$\chi^2=\sum_{i=1}^{n}|\Re_i(d;k_i)-\Re_i(k_i)_{\mathrm{sam}}|^2. \tag{3}$$

The search for the true value of d needs to be made numerically using an appropriate one-dimensional nonlinear least-squares technique, for which the well-established Levenberg-Marquardt algorithm[11] was used in this investigation.

Now, the second step of measurement is to determine the top surface height h, which is performed with the shutter being off. In this case, the spectrometer provides the spectral density of the mutual interference between the reference and measurement waves. To extract the phase information $\Phi(h,d;k)$, the measured intensity data are Fourier transformed with subsequent isolation of the dominant peak using a narrow-band spatial filter.[9] Then, the isolated peak is inverse Fourier transformed, from which the phase $\Phi(h,d;k)$ is readily recovered. As the measured phase $\Phi(h,d;k)$ is the sum of $2kh$ and $\Psi(d;k)$, the top surface height is determined as

$$h=\frac{1}{2}\frac{\mathrm{d}[\Phi(h,d;k)-\Psi(\mathrm{d};k)]}{\mathrm{d}k}. \tag{4}$$

Note that $\Psi(d;k)$ is computed by substituting the true value of d into Eq. (1) so that the top surface height h is determined from Eq. (4).

A measurement result is shown in Fig. 2, which was taken from a SiO_2 thin-film layer deposited over a tungsten metal structure fabricated on a silicon substrate with subsequent planarization by adopting the chemical-mechanical-

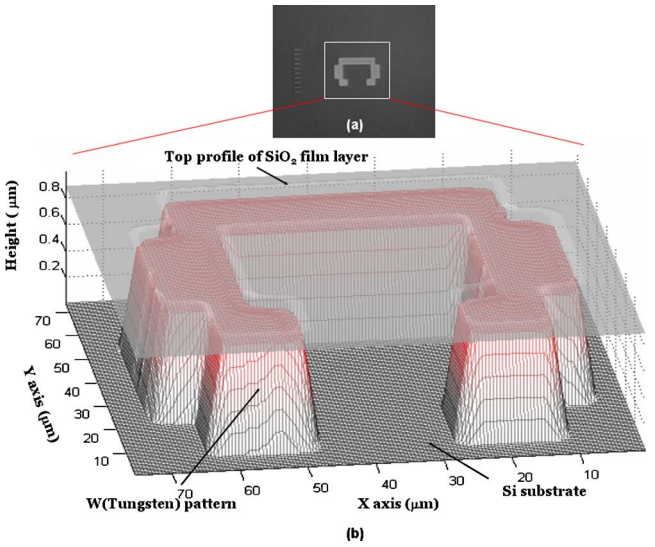

FIG. 2. (Color online) Measurement result: (a) top view of the specimen and (b) 3D thickness profile of a SiO_2 film layer deposited over a tungsten structure of "C" shape fabricated on a Si substrate.

TABLE I. Details of the apparatus used for experiments.

Objectives for specimen and reference	20× with 0.4 NA
Collimated source beam	~15 mm in diameter
Illuminated area on specimen	~0.6 mm in diameter
Spectral range of spectrometer grating	360–820 nm
Spectral resolution of spectrometer grating	3 nm
Charge-coupled device camera for spectroscopic sampling	640×480 pixels
Shutter speed	30 frames/s
Computational time per point	60 ms with MATLAB

polishing (CMP) process. Details regarding the apparatus used for the measurements are summarized in Table I. The measured film thickness ranges from a few nanometers to ~800 nm, of which 3D tomographical view is clearly seen along with the top and bottom boundaries of a film layer at the same time. This experimental result demonstrates that the proposed method is capable of reconstructing the 3D tomographical map of very thin-film layers of less than 0.1 μm thickness with the depth resolution in the nanometer range. The lateral resolution is determined by the diffraction limit of the objective lens in use, which is found ~0.5 μm in the measurement.

Figure 3 presents another test result in which a series of measurements was taken consecutively with varying time delays from a specimen of SiO_2 film that was subject to the CMP process. The initial film thickness was ~200 nm and its variation during the CMP process was monitored with depth resolution in the nanometer range until it was completely removed from the silicon substrate. The measurement result clearly shows a tomographic view, indicating how the film thickness reduces gradually as the CMP process proceeds. Finally, the measurement accuracy of the proposed method was verified through a comparison with an ellipsometry-based instrument by gauging standard specimens of various different film thicknesses. As listed in Table II, the comparison confirms that the maximum mean deviation between the two measurements lies within a small difference of ~1 nm with almost identical standard deviations.

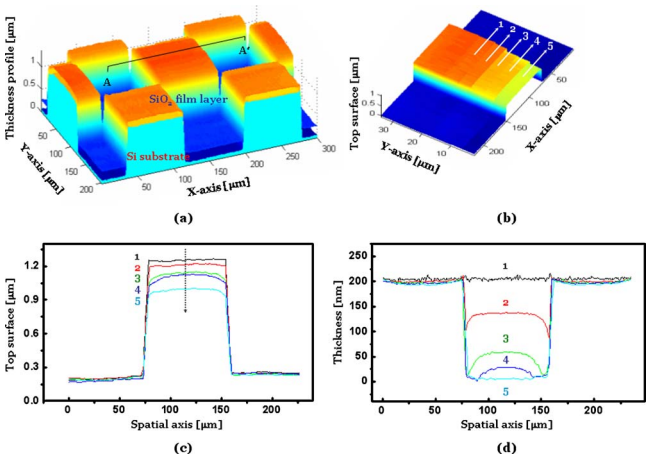

FIG. 3. (Color online) Series of consecutive measurements: (a) 3D tomographical thickness profile of a SiO_2 film layer deposited on a check-patterned Si substrate (before CMP process), (b) variation of the top surface profile of A-A' line along with various time elapses of CMP process; 1: 0 s, 2: 15 s, 3: 30 s, 4: 40 s, and 5: 50 s, (c) cross sectional top surface profiles of A-A' line with time elapse of CMP process, and (d) cross sectional film thickness of A-A' line with time elapse of CMP process.

TABLE II. Comparison measurements of a standard specimen.

Sample	Film thickness measured by ellipsometry (mean±σ) (nm)	Film thickness measured by proposed method (mean±σ) (nm)
1	28.3±0.2	27.9±0.5
2	111.7±0.05	111.0±0.2
3	207.0±0.1	207.0±0.1
4	514.9±0.5	515.1±0.4

In summary, we have proposed and tested a method of spectrally resolved white-light interferometry to measure 3D tomographical profile measurements of thin-film layers. Actual implementation of the proposed method was demonstrated through a dispersive scheme of white-light interferometer that allows for decoupled measurements of the film thickness and top surface height at the same time. Test results confirmed that the proposed method is capable of gauging very thin films of only a few nanometer thickness, being well suited for the in-line high-speed inspection of microelectronics devices.

This work was supported by the Creative Research Initiatives Program of the Ministry of Science and Technology in the Republic of Korea.

[1] R. M. A. Azzam and N. M. Bashara, *Ellipsometry and Polarized Light* (North-Holland, New York, 1979).
[2] P. S. Hauge, Surf. Sci. **96**, 108 (1980).
[3] H. G. Tompkins and W. A. McGahan, *Spectroscopic Ellipsometry and Reflectometry: A User's Guide* (Wiley, New York, 1999).
[4] A. Rosencwaig, J. Opsal, D. L. Willenborg, S. M. Kelso, and J. T. Fanton, Appl. Phys. Lett. **60**, 1301 (1992).
[5] M. Fury, Solid State Technol. **38**, 47 (1995).
[6] D. Boning, A. Hurwitz, J. Moyne, W. Moyne, S. Shellman, T. Smith, J. Taylor, and R. Telfeyan, IEEE Trans. Compon., Packag., Manuf. Technol., Part C **19**, 307 (1996).
[7] S.-W. Kim and G.-H. Kim, Appl. Opt. **38**, 5968 (1999).
[8] D. Kim, S. Kim, H. J. Kong, and Y. Lee, Opt. Lett. **27**, 1893 (2002).
[9] Y.-S. Ghim and S.-W. Kim, Opt. Express **14**, 11885 (2006).
[10] S. K. Debnath, M. P. Kothiyal, J. Schmidt, and P. Hariharan, Opt. Express **14**, 4662 (2006).
[11] The Levenberg-Marquardt function is available as LEASTSQ in the MATLAB software.