Thin Solid Films 584 (2015) 176–185

Contents lists available at ScienceDirect

Thin Solid Films

journal homepage: www.elsevier.com/locate/tsf

Review

Development of a broadband Mueller matrix ellipsometer as a powerful tool for nanostructure metrology

Shiyuan Liu *, Xiuguo Chen, Chuanwei Zhang

State Key Laboratory of Digital Manufacturing Equipment and Technology, Huazhong University of Science and Technology, Wuhan, Hubei 430074, China

A R T I C L E I N F O

Available online 10 February 2015

Keywords:
Mueller matrix ellipsometry
Mueller matrix polarimetry
Depolarization
Optical scatterometry
Computational metrology
Optical metrology
Nanometrology
Nanostructure

A B S T R A C T

Ellipsometric scatterometry has gained wide industrial applications in semiconductor manufacturing after ten years of development. Among the various types of ellipsometers, Mueller matrix ellipsometer (MME) can provide all 16 elements of the 4 by 4 Mueller matrix, and consequently, MME-based scatterometry can acquire much more useful information about the sample and thereby can achieve better measurement sensitivity and accuracy. In this paper, the basic principles and instrumentation of MME are presented, and the data analysis in MME-based nanostructure metrology is revisited from the viewpoint of computational metrology. It is pointed out that MME-based nanometrology is essentially a computational metrology technique by modeling a complicated forward process followed by solving a nonlinear inverse problem. Several case studies are finally provided to demonstrate the potential of MME in nanostructure metrology.

Contents

1. Introduction

Nanomanufacturing is referred to as the manufacturing of products with feature dimensions at the nanometer scale. It is an essential bridge between the newest discoveries of fundamental nanoscience and real-world products by nanotechnology. One critical challenge to the realization of nanomanufacturing is the development of necessary instrumentation and metrology at the nano-scale, especially the fast, low-cost, and non-destructive metrology techniques that are suitable in high-volume nanomanufacturing [1]. Although scanning electron microscopy (SEM), atomic force microscopy (AFM), or transmission electron microscopy (TEM) can provide high precision data, they are, in general, time-consuming, expensive, complex to operate, and problematic in realizing in-line integrated measurement.

Ellipsometry is an optical metrology technique that utilizes polarized light to characterize thickness of thin films and optical constants of both layered and bulk materials [2]. Since the year of around 2000,

* Corresponding author at: State Key Laboratory of Digital Manufacturing Equipment and Technology, Huazhong University of Science and Technology, 1037 Luoyu Road, Wuhan, Hubei 430074, China. Tel.: +86 27 8755 9543; fax: +86 27 8755 8045.
E-mail address: shyliu@hust.edu.cn (S. Liu).

http://dx.doi.org/10.1016/j.tsf.2015.02.006
0040-6090/

spectroscopic ellipsometry (SE) was introduced to monitor the critical dimension (CD) of grating structures in semiconductor manufacturing [3–5]. Compared with SEM, AFM, and TEM, this technique, also referred to as optical scatterometry or optical critical dimension metrology, has achieved wide industrial applications after ten years of development due to its attractive advantages, such as low cost, high throughput, and minimal sample damage [6,7].

The application of ellipsometry for nanostructure metrology heavily relies on two key issues [8], i.e., the collection of a precise measured signature of a diffractive nanostructure as well as the fast and accurate reconstruction of the structural profile from the measured signature. The reconstruction of the structural profile from the measured signature is a typical inverse diffraction problem with an objective of finding a profile whose theoretical signature can best match the measured one. The solution of the inverse problem usually employs two kinds of methods [9], namely the nonlinear regression method [10,11] and the library search method [12–14]. Both of these two approaches involve the establishment of a theoretical diffraction model that relates the optical signatures and the structural profiles associated with these signatures. Many methods have been proposed to solve this diffraction model [15], of which the rigorous-coupled wave analysis (RCWA) [16–18] is the most common approach in optical scatterometry. The collection of the measured signature involves the development of a specific ellipsometer. Among the various types of ellipsometers, Mueller matrix ellipsometer (MME), also known as Mueller matrix polarimeter, can provide all 16 elements of the 4×4 Mueller matrix in each measurement. Compared with conventional ellipsometric scatterometry, which at most obtains two ellipsometric angles, MME-based scatterometry can acquire much more useful information about the sample, such as anisotropy and depolarization. Therefore, MME is expected to be a powerful tool for nanostructure metrology in high-volume nanomanufacturing.

Several researchers have investigated the MME-based nanostructure metrology over the past years [19–25]. Novikova et al. implemented MME in different azimuthal angles to characterize one-dimensional diffraction gratings [19,20]. It was shown that the Mueller matrices measured in proper conical diffraction configurations may help decouple some of the fitting parameters. We further proposed a measurement configuration optimization method for MME to find an optimal combination of the incidence and azimuthal angles, with which more accurate measurement can be achieved [21]. Kim and Li et al. investigated the possibility of measuring overlay and grating asymmetry with MME [22,23]. Their research indicated that MME had good sensitivity to both the magnitude and direction of overlay and profile asymmetry, while conventional ellipsometric scatterometry had difficulty in distinguishing the direction of the above features. In our recent work, noticeable depolarization effects were observed from the measured Mueller matrices of nanoimprinted resist patterns [24,25]. We found that improved accuracy can be achieved for the line width, line height, sidewall angle, and residual layer thickness measurement after taking depolarization effects into account.

In this paper, we will review the principles and potential of MME in nanostructure metrology to provide a complete picture of this technique. We will first introduce the basic principles and instrumentation of MME, with a demonstration of the development of a broadband dual rotating-compensator Mueller matrix ellipsometer in our lab. Then we will revisit the data analysis in MME-based nanostructure metrology from the viewpoint of computational metrology [26,27], and point out that MME-based nanometrology is essentially a computational metrology technique by modeling a complicated forward process followed by solving a corresponding nonlinear inverse problem. Finally, we will present several case studies in MME-based nanostructure metrology, including the measurement of e-beam patterned grating structures, the measurement of nanoimprinted resist patterns, the measurement of lithographic patterns with line edge roughness (LER), and the measurement of etched trench nanostructures that are typically encountered in the manufacturing of flash memory storage cells, to demonstrate the capability of MME in nanostructure metrology.

2. Fundamentals

2.1. Basic principles and instrumentation of MME

The measurement of Mueller matrix involves a series of K ($K \geq 16$) flux measurements made by illuminating the sample with different polarization states and analyzing the exiting beam with different analyzers. The k-th measured flux g_k is related to the sample Mueller matrix $\mathbf{M}$ by [28]

$$g_k = \mathbf{A}_k^{\mathrm{T}}\mathbf{M}\mathbf{S}_k = (\mathbf{S}_k \otimes \mathbf{A}_k)^{\mathrm{T}}\mathbf{m}, \qquad 1 \leq k \leq K, \tag{1}$$

where the symbol ⊗ denotes the Kronecker product, the superscript “T” denotes the transpose. $\mathbf{S}_k$ is the k-th incident polarization state produced by the polarization state generator (PSG), and $\mathbf{A}_k$ is the k-th exiting polarization state produced by the polarization state analyzer (PSA). $\mathbf{m}$ is a 16×1 Mueller vector obtained by reading the sample Mueller matrix elements in the lexicographic order, i.e., $\mathbf{m} = [M_{11}, M_{12}, M_{13}, M_{14}, M_{21}, M_{22}, \ldots, M_{44}]^{\mathrm{T}}$. Eq. (1) can be written in a matrix form as

$$\mathbf{G} = \mathbf{D}\mathbf{m}, \tag{2}$$

where $\mathbf{G}$ is a $K \times 1$ column vector with the k-th element being g_k, and $\mathbf{D}$ is a $K \times 16$ matrix with the k-th row vector being $(\mathbf{S}_k \otimes \mathbf{A}_k)^{\mathrm{T}}$. According to Eq. (2), the sample Mueller matrix can be measured by

$$\mathbf{m} = \mathbf{D}^{+}\mathbf{G}, \tag{3}$$

where $\mathbf{D}^{+} = (\mathbf{D}^{\mathrm{T}}\mathbf{D})^{-1}\mathbf{D}^{\mathrm{T}}$ is the Moore–Penrose pseudo-inverse of matrix $\mathbf{D}$. Eq. (3) is the basic and general principle of sample Mueller matrix measurement for any type of Mueller matrix ellipsometers, such as the Mueller matrix ellipsometer based on the coupled ferroelectric liquid crystal cell [29,30], the dual rotating-compensator [31,32], or the four photoelastic modulators [33]. The dual rotating-compensator configuration was adopted in the development of the Mueller matrix ellipsometer in our lab.

Specifically, as schematically shown in Fig. 1, the basic system layout of the dual rotating-compensator Mueller matrix ellipsometer in order of light propagation is $\mathrm{PC_{r1}}(\omega_1)\mathrm{SC_{r2}}(\omega_2)\mathrm{A}$, where P and A stand for the polarizer and analyzer, $\mathrm{C_{r1}}$ and $\mathrm{C_{r2}}$ refer to the 1st and 2nd rotating compensators, and S stands for the sample. The fast axis angles C_1 and C_2 of the 1st and 2nd compensators rotate synchronously at $\omega_1 = 5\omega$ and $\omega_2 = 3\omega$, where ω is the fundamental mechanical frequency. The Stokes vector $\mathbf{S}_{\mathrm{out}}$ of the exiting light beam can be expressed as the following Mueller matrix product [25,32]

$$\mathbf{S}_{\mathrm{out}} = [\mathbf{M}_{\mathrm{A}}\mathbf{R}(A)][\mathbf{R}(-C_2)\mathbf{M}_{\mathrm{C2}}(\delta_2)\mathbf{R}(C_2)]\mathbf{M}[\mathbf{R}(-C_1)\mathbf{M}_{\mathrm{C1}}(\delta_1)\mathbf{R}(C_1)][\mathbf{R}(-P)\mathbf{M}_{\mathrm{P}}\mathbf{R}(P)]\mathbf{S}_{\mathrm{in}}, \tag{4}$$

where $\mathbf{M}_i$ ($i = \mathrm{P, A, C1, C2}$) is the Mueller matrix associated with each optical element. $\mathbf{R}(\alpha)$ is the Mueller rotation transformation matrix for rotation by the angle α [$\alpha = P, A, C_1$, and C_2] that describes the corresponding orientation angle of each optical element. δ_1 and δ_2 are the wavelength-dependent phase retardances of the 1st and 2nd rotating compensators. By multiplying the matrices in Eq. (4), we can obtain the following expression for the irradiance at the detector (proportional to the first element of $\mathbf{S}_{\mathrm{out}}$) [32]

$$\begin{aligned} I(t) &= I_{00}M_{11}\left\{a_0 + \sum_{n=1}^{16}[a_{2n}\cos(2n\omega t - \phi_{2n}) + b_{2n}\sin(2n\omega t - \phi_{2n})]\right\} \\ &= I_0\left\{1 + \sum_{n=1}^{16}[\alpha_{2n}\cos(2n\omega t - \phi_{2n}) + \beta_{2n}\sin(2n\omega t - \phi_{2n})]\right\}, \end{aligned} \tag{5}$$