

Specular Spectroscopic Scatterometry in DUV Lithography

Xinhui Niu

Timbre Technology, Inc., CA 94538 and U.C.Berkeley, CA 94720

Nikhil Jakatdar, Junwei Bao, Costas Spanos

U.C.Berkeley, CA 94720

Sanjay Yedur

Advanced Micro Devices, Sunnyvale, CA 95052 and SEMATECH, Austin, TX 78741

ABSTRACT

Scatterometry is one of the few types of metrology that has true *in-situ* potential for deep submicron CD and profile analysis. To date, commercial prototypes have been used to establish scatterometry based on single wavelength, multiple incident angle inspection. We extend this idea by deploying specular spectroscopic scatterometry (SSS). Conventional scatterometry is designed to measure either many diffraction orders or variable incident/collection angles at a single wavelength. Specular spectroscopic scatterometry is designed to measure the 0th order diffraction responses at a fixed angle of incidence. Specular spectroscopic scatterometry can make direct use of the existing spectroscopic ellipsometry equipment. We show that SSS provides an accurate, inexpensive, and non-destructive CD metrology solution.

Keywords: Specular spectroscopic scatterometry, DUV lithography, diffraction grating, spectroscopic ellipsometry.

1. INTRODUCTION

Physical metrology is the key element in maintaining an adequate and affordable process latitude in lithography processing. Accurate metrology is needed for characterizing and monitoring the processing states, such as exposure, focus, post-exposure-bake (PEB), critical dimension (CD) resolution, etc. Various techniques have been both proposed and implemented for these purposes. Visual test based methods have played significant roles in both production and development environments. For example, the use of checking completely developed and cleared photoresist patterns from a dose-focus matrix is very common in the semiconductor industry. While visual tests are easy to implement, they are not easy to automate. Scanning electron microscopes (SEM) and atomic force microscopes (AFM) can deliver direct images of the patterned features. However, they are very expensive, and can be either time-consuming or destructive, and thus not suitable for run-to-run monitoring. Electrical measurements can provide information on final CD linewidths, but cannot be used *in-situ*, and cannot provide reliable resist profile information.

A number of methods have been proposed for lithography process metrology. Nyysönen and Kirk presented a monochromatic waveguide model that can predict the optical microscope images of line objects with arbitrary edge geometry [1]. The model is used to illustrate the effects of line edge structure on the optical image. Yuan and Strojwas developed a simulator called “METRO” to obtain more accurate alignment [2]. Tadros, Neureuther and Guerrieri used a massively parallel computer simulation algorithm to investigate electromagnetic scattering and optical imaging issues related to linewidth measurement of pol-

ysilicon gate structures [3]. Jakatdar *et al.* noticed that photoresist deprotection is related to resist film shrinkage, thus they proposed a metrology based on deprotection induced thickness loss (DITL) [4]. Using reflectometry, Ziger correlated ultraviolet reflectance spectra to the linewidth of i-line photoresist [5]. These methods intend to characterize the process from the correlation between optical responses and the process conditions. Usually these methods deliver the effective linewidth values. However, the actual CD profile information is needed because it contains information about the overall lithography quality.

Scatterometry is based on the reconstruction of the grating profile from its optical diffraction response. McNeil, Naqvi and co-workers have developed and demonstrated that scatterometry can be used for 0.5 μm CD characterization [6]. We call this type of design “conventional scatterometry”. Conventional scatterometry tends to employ a single wavelength, variable angle readings. The disadvantage of this type of metrology is the use of a single wavelength and the mechanical complexity of the detection scheme.

In contrast to conventional scatterometry, the specular spectroscopic scatterometry we introduce is designed to measure the 0th order diffraction at a fixed incident angle. The term “spectroscopic” means that multiple wavelengths are under consideration. Due to its fixed angle, specular spectroscopic scatterometry can make use of a existing spectroscopic ellipsometer, and can be easily installed *in-situ*.

One reason to pursue the single wavelength, variable angle scatterometry setup is that the higher order diffraction can be measured. However, as the CD reduces, higher diffraction orders can become all evanescent (not measurable at far field). For example, using the scatterometer with He-Ne laser (632.8nm), only 0th order is propagating when the pitch of grating is less than 316.4nm. Under this circumstance, conventional scatterometry can only measure 0th order diffraction. By simulation study and preliminary experiment results, we will show that specular spectroscopic scatterometry has better accuracy, and can also be used for *in-situ* applications.

2. ELECTROMAGNETIC RESPONSE SIMULATION OF GRATINGS WITH DIFFERENT PROFILES

Rigorous Coupled-Wave Analysis (RCWA) is one of the most widely used methods for the accurate analysis of the diffraction by periodic gratings [6]. A lot of theoretical work has been done since RCWA was first formulated in early 80s. We have implemented the Grating ToolKit (*gtk*), a C++ numerical package, which absorbs some of the most important ideas of these works. The current version of *gtk* implements several flavors of RCWA for one-dimensional (1D) gratings, including TE, TM and conical polarization. By using advanced numerical techniques and network of workstations (NOW) [8], *gtk* can efficiently simulate considerably complicated CD profiles [9].

Even though we only measure the 0th order, many orders must be taken into account during the simulation. To obtain accurate simulation on the grating structures in this paper, it is determined that about 30 orders in TE polarization and 40 orders in TM polarization must be retained in RCWA.

3. SPACULAR SPECTROSCOPIC SCATTEROMETRY SETUP

Specular spectroscopic scatterometry measures the 0th order diffraction responses of a grating at multiple wavelengths. Given the 0th order diffraction responses, one can then attempt to reconstruct the grating profile. Conventional spectroscopic ellipsometry equipment can be directly used in this type of metrology. In other words, we do not need special equipment for specular spectroscopic scatterometry, as the cost of hardware is shifted to software.

Compared to single-wavelength, variable-angle scatterometry, specular spectroscopic scatterometry has the advantage of the additional information contained in the spectral component. A spectroscopic ellipsometer is used in this work for 1D gratings, shown in FIGURE 1. With this configuration, the ratio of the 0th order complex transverse electric (TE) and transverse magnetic (TM) reflectivity $\rho = r_{p,0}/r_{s,0} = \tan\Psi e^{i\Delta}$ is measured, where $r_{p,0}$ is the 0th order TM reflectance coefficient and $r_{s,0}$ is the 0th order TE reflectance coefficient. Using a spectroscopic ellipsometer has two advantages. First, the measurement of the ratio of TE *and* TM provides more sensitivity than just using the measurement of TE *or* TM. Second, we can make direct use of an existing ellipsometer in the fab, hence avoiding the additional hardware expense.

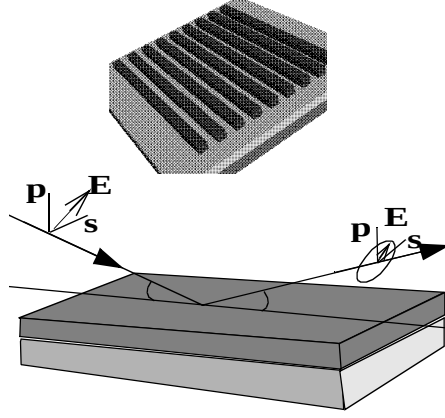


FIGURE 1 Specular spectroscopic scatterometry for 1D gratings.

4. A LIBRARY-BASED METHODOLOGY FOR CD PROFILE EXTRACTION

The extraction of a CD profile can be viewed as an optimization problem. The objective is to find a profile whose simulated diffraction responses match the measured responses. Optimization techniques, such as simulated annealing and gradient based optimization techniques, can be applied. However, for complicated profiles, it is computationally prohibitive to exhaustively search for the optimal profiles during the measurement. The feasible way for the *in-situ* requirement is to generate the simulation responses before the measurement. A library based methodology for CD profile extraction is proposed in this work. FIGURE 2 describes the extraction flow.

First, mask information, technology characteristics, and thin-film information (optical properties n , k and thickness values) are used to obtain a collection of profiles. The profile information includes the information of the grating layer and all the underneath layers. The profiles can be obtained by a random profile generator. The collection of profiles should be sufficient and

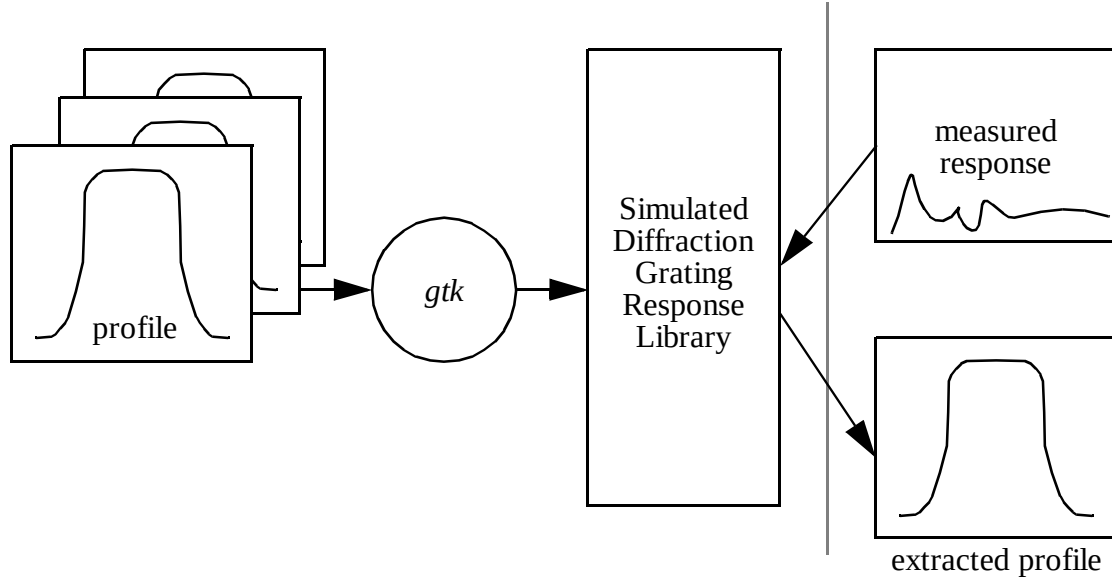


FIGURE 2 A library-based methodology for CD profile extraction.

efficient. *Sufficient* means that there should be enough profiles in the library for most possible process results, *efficient* means that there should not be too many profiles in the library.

Second, the collection of profiles are used as inputs to a diffraction grating simulator, such as *gtk*, to generate the simulated diffraction responses. Usually the diffraction efficiencies, $\tan\Psi$ and $\cos\Delta$ are simulated over a wide range of wavelengths.

For *in-situ* specular spectroscopic scatterometry use, the diffraction responses are measured and compared with the library. When the library is complete, there will be one or more profiles whose simulated responses match those of the measured sample. The key of the success for this library-based extraction methodology is the completeness of the library combined with efficient search methods.

The uniqueness of solution is an issue in this approach. In other words, it is possible that two different profiles may lead to similar diffraction responses. We will address this problem experimentally.

5. EXPERIMENTAL VERIFICATION

The experimental verification of specular spectroscopic scatterometry consists of two parts: the verification of the forward diffraction grating simulation from given CD profiles and the verification of the inverse CD profile extraction from the scatterometry measurement.

In this section, we consider a focus-exposure matrix experiment. As shown in FIGURE 3 we have 5 focus settings and 7 dose settings. The dose settings are coded as -3, -2, -1, 0, 1, 2, and 3, indicating the values from 11.5 mJ/cm^2 to 14.5 mJ/cm^2 in steps of 0.5 mJ/cm^2 . The focus settings are coded as -2, -1, 0, 1, and 2, indicating the values from $-0.2 \text{ }\mu\text{m}$ to $0.2 \text{ }\mu\text{m}$ in steps of $0.1 \text{ }\mu\text{m}$.

In total we have 31 settings on each wafer. The mask has $0.28\mu\text{m}/0.28\mu\text{m}$ line/space gratings. The thin-film stack includes DUV photoresist Shipley UV5, a type of anti-reflection coating (ARC) and a silicon substrate. After exposure and PEB, UV5 was developed to form $200\mu\text{m}$ -by- $200\mu\text{m}$ grating regions. A KLA-Tencor Prometrix® UV-1280SE was used to measure the ratio of 0th order TE and TM fields. The incident angle is 70.5° . The light beam was focused on a $30\mu\text{m}$ -by- $70\mu\text{m}$ spot within the grating region.

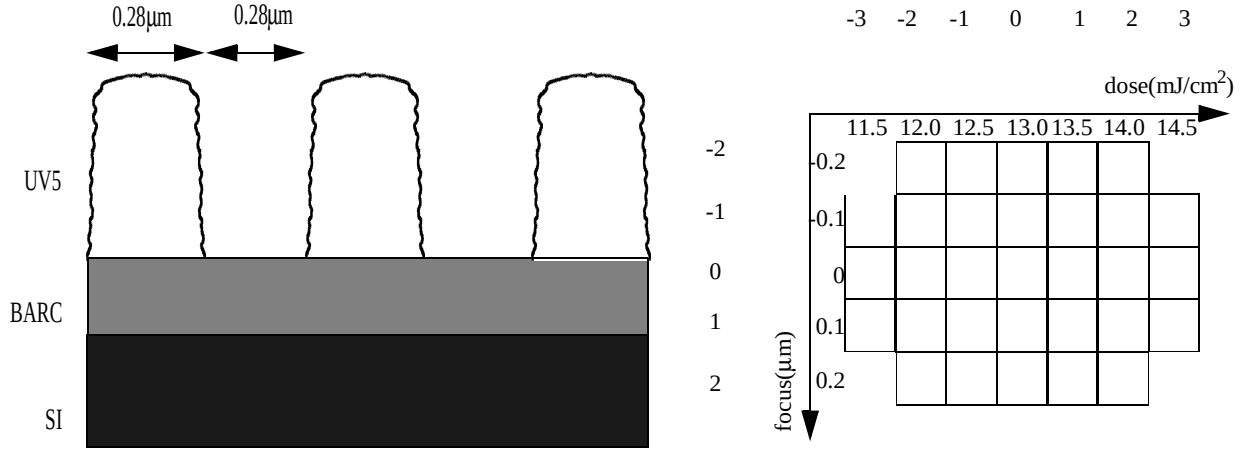


FIGURE 3 A focus-exposure matrix experiment for verification.

FIGURE 4 shows the measured $\tan\Psi$ and $\cos\Delta$ of each die in the entire wafer. It is interesting to notice that different grating profiles generate significantly different $\tan\Psi$, even at higher wavelengths (compared to the CD linewidth). The same behavior is also observed for $\cos\Delta$.

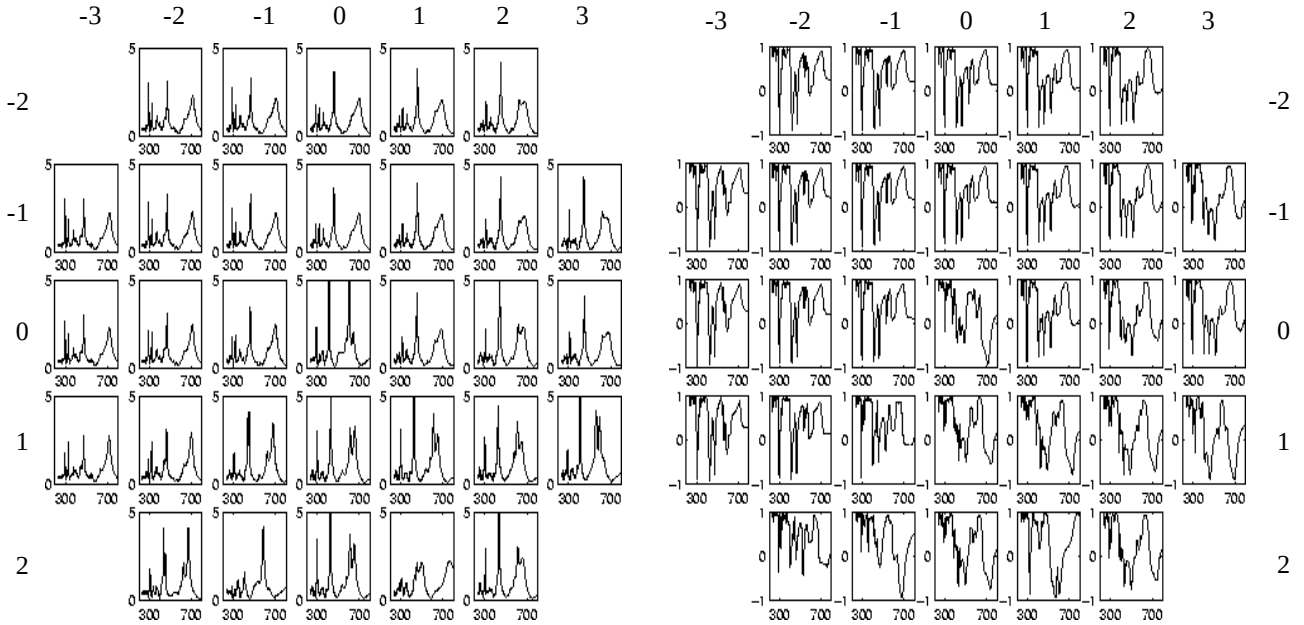


FIGURE 4 $\tan\Psi$ and $\cos\Delta$ of the entire focus-exposure matrix.

To verify the forward diffraction grating simulation, we use the AFM to measure several structures from the dose-focus matrix. FIGURE 5 is the calibrated CD profile of dose level -1 and focus level -1. To approximate this complicated profile, the photoresist is sliced into 100 layers. The optical properties of photoresist and ARC are shown in FIGURE 6. The thickness of ARC is 162.9nm. There are 31 TE and 41 TM orders retained in the RCWA simulation. The diffracted fields are calculated from 240nm to 800nm wavelength with 1nm resolution. FIGURE 7 shows the measured and simulated $\tan\Psi$ and $\cos\Delta$ from this grating profile. We can see that the simulated and measured diffracted fields match very well.

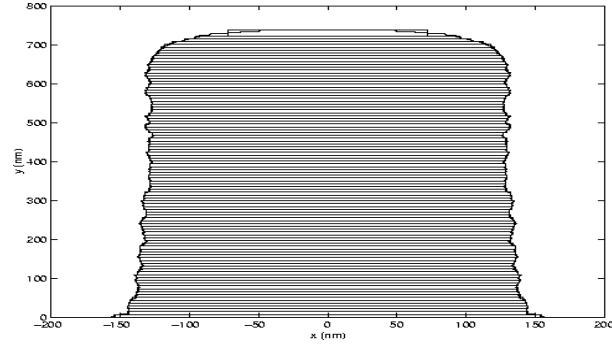
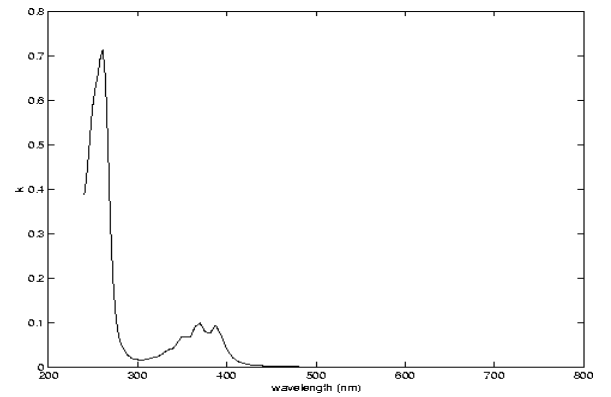
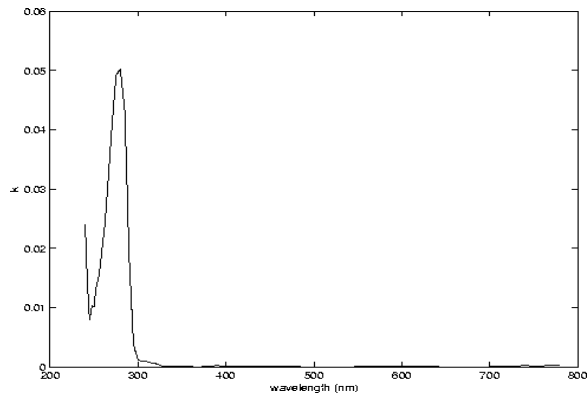
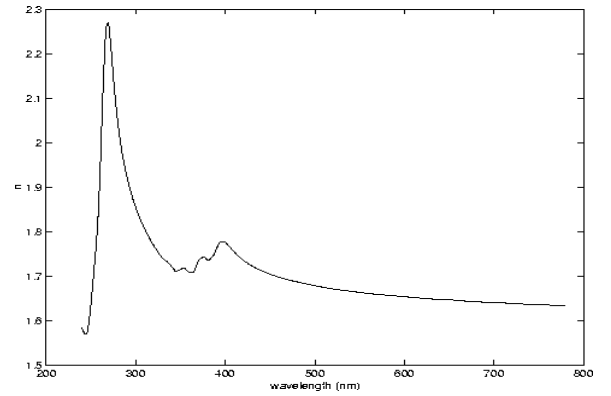
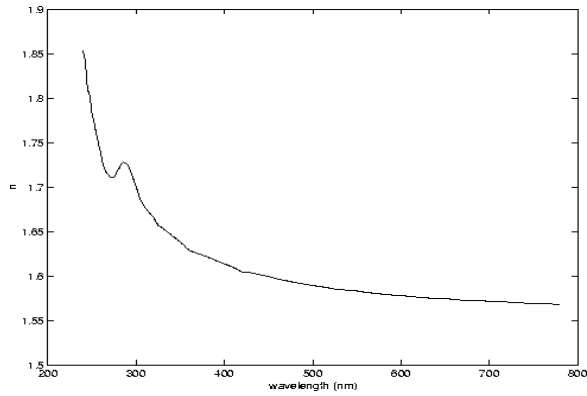


FIGURE 5 Calibrated CD AFM profile of the dose level -1 and focus level -1.



(a)

(b)

FIGURE 6 The optical properties of the UV5 (a) and ARC (b) in the experiment.

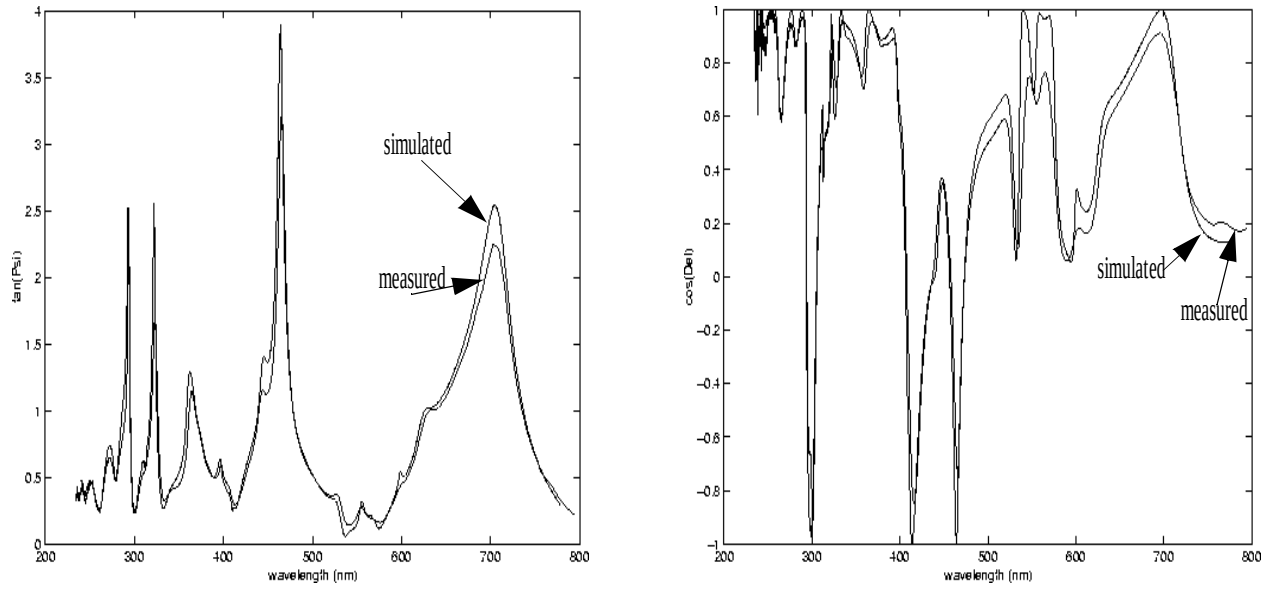


FIGURE 7 Measured and simulated $\tan\Psi$ and $\cos\Delta$ from the AFM CD profile.

The library-based CD profile extraction methodology described in section 4 is implemented. A profile library is randomly generated from a set of profile primitives. Shown in FIGURE 8, a profile consists of three parts, the top, the middle and the bottom. We have about 30 pre-defined “shapes” for these three parts. These pre-defined “shapes” are also called profile primitives. To generate a profile, we randomly select a primitive for top, middle and bottom. Each primitive is further scaled by two random scaling parameters to control the width and thickness. The ARC thickness is also randomly generated to accommodate the process variation. There are 19 total layers for the photoresist and 1 layer for the ARC.

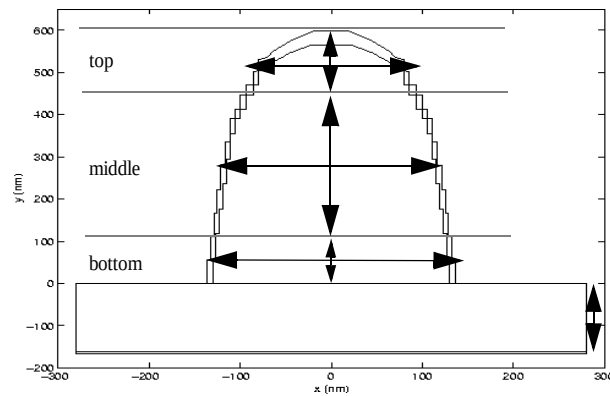


FIGURE 8 Random CD profile library generation.

About 180,000 profiles are generated, and corresponding diffraction responses are simulated by *gtk*. Because of the computational cost, each grating profile is simulated every 10nm from 240nm to 780nm, step of 10nm. The numbers of retained orders for TE and TM are 31 and 41, respectively. Using *gtk*, the simulation for one profile, which includes both TE and TM on 53 wavelengths, takes approximately 2 minutes on a Sun Ultra I 167MHz workstation.

To extract the CD profile from a measurement, the measured $\tan\Psi_{\text{measured}, \lambda}$ and $\cos\Delta_{\text{measured}, \lambda}$ are compared with each simulated $\tan\Psi_{\text{theoretical}, \lambda}$ and $\cos\Delta_{\text{theoretical}, \lambda}$ in the library. If there is a “good” match between the measured and simulated signals, the corresponding CD profile is considered as the extracted profile. Mathematically, this problem is formulated as

$$\min \left\{ \sum_{\lambda} ((\tan\Psi_{\text{measured}, \lambda} - \tan\Psi_{\text{theoretical}, \lambda})^2 + (\cos\Delta_{\text{measured}, \lambda} - \cos\Delta_{\text{theoretical}, \lambda})^2) \right\}. \quad (1)$$

For example, for the focus-exposure matrix shown in FIGURE 4, given the $\tan\Psi$ and $\cos\Delta$ signal at focus level -1 and exposure level -1, we found several close “matches”. We did not just choose the closest match because we want to examine the uniqueness problem. FIGURE 9 shows the matched simulated and measured signals. FIGURE 10 compares the extracted profiles to the AFM measurement. There are two observations. First, the AFM measurement agrees with those extracted profiles; second, similar diffraction responses also have similar grating profiles. FIGURE 11 shows the comparison between the extracted profiles and AFM measurements across the whole focus-exposure matrix.

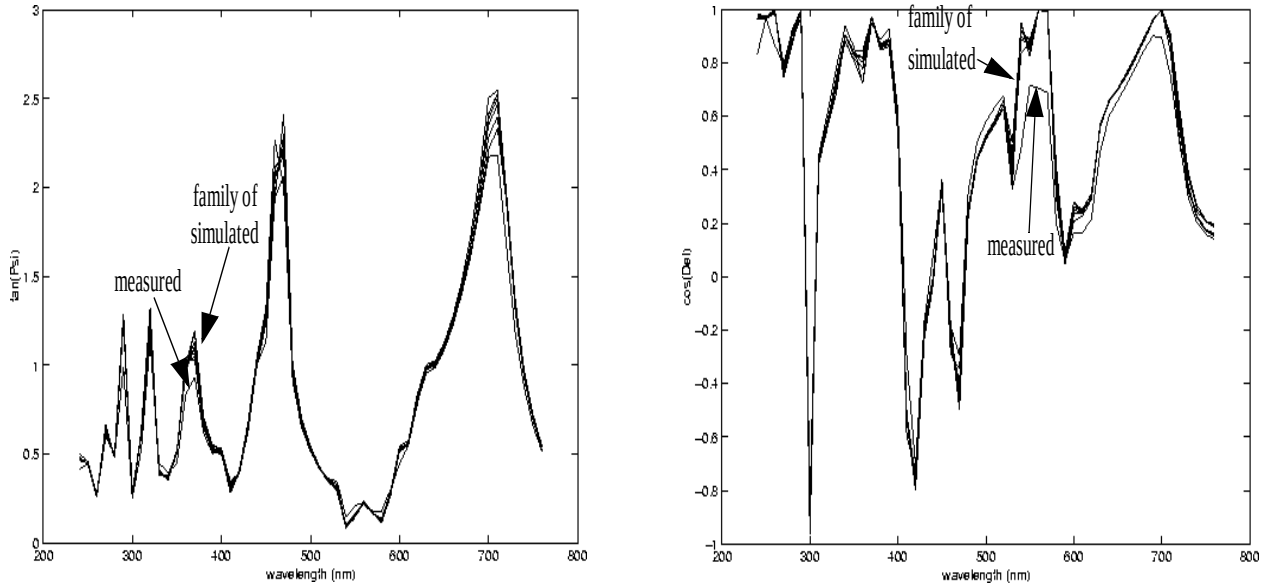


FIGURE 9 Matching on the simulated and measured $\tan\Psi$ and $\cos\Delta$ signals on the die of dose level -1 and focus level -1.

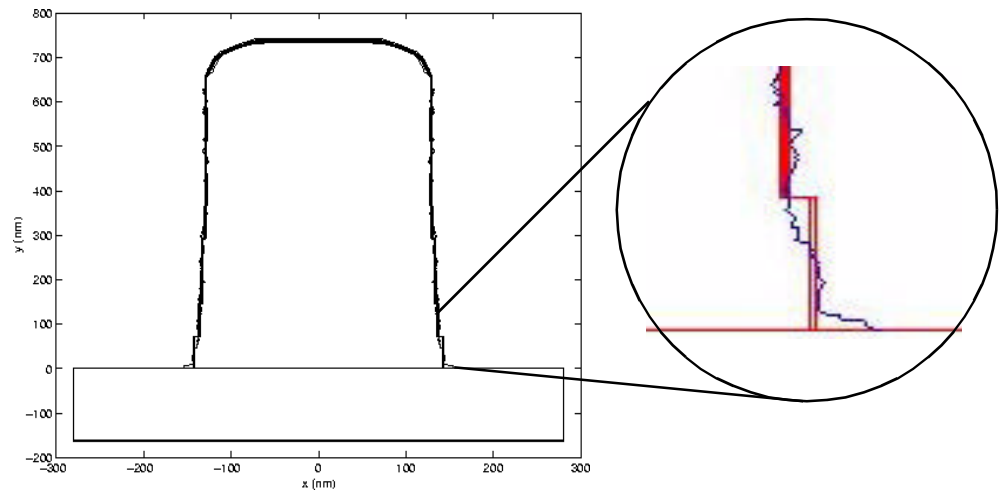


FIGURE 10 Comparison between the extracted CD profiles and the CD-AFM profile.

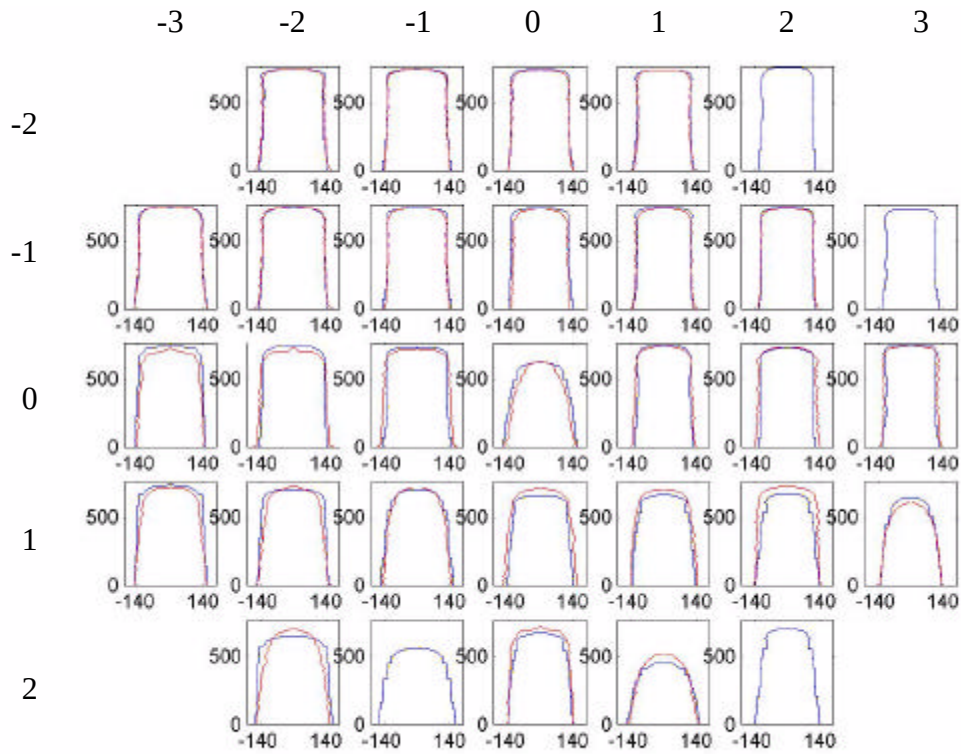


FIGURE 11 Comparison between the extracted grating profiles and the CD-AFM profiles across the focus-exposure matrix. The four AFM profiles with (dose, focus) level of (2,-2), (3,-1), (-1,2) and (2,2) have not been measured.

6. CONCLUSIONS

With the progress of deep sub-micron technology, the accuracy and efficient measurement of parameters such as the line width, height/depth and side-wall profile are becoming increasingly critical to develop and characterize lithography processes. In this paper, we propose a specular spectroscopic scatterometry application for in-situ DUV lithography, which includes using RCWA to simulate the electromagnetic response of gratings with different profiles and using spectroscopic ellipsometry to measure 1D gratings. A library-based methodology for profile extraction is proposed and implemented. A focus-exposure matrix experiment is used for the verification. This metrology can be used with current technology, and it is expected to be able to extend to the 0.1 μ m generation [9]. The significance of this work is that we shift the complexity of metrology from specialized hardware, such as CD-SEM, to sophisticated data analysis in conjunction with existing equipment, such as spectroscopic ellipsometers.

7. ACKNOWLEDGEMENTS

This work was supported by the MICRO program under contract #97-167, and by the UC-SMART program under contract #MP97-1.

8. REFERENCES

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