Assessing Quantitative Optical Imaging for Realizing In-die Critical Dimension Metrology

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INTRODUCTION

The need for accurate critical dimension (CD) measurements as dimensions decrease for semiconductor manufacturing is now more acute with the ubiquitous challenge of reconstructing 3-D nanostructures. While optical methods are uniquely positioned as the high-throughput solution for process control due to their relative high speed and low cost, methods for sidestepping optical diffraction limits must be further advanced to meet industry needs. Our group at the National Institute of Standards and Technology (NIST) has recently demonstrated the capability of measuring finite sets of features of 15 nm-scale CD within a high-magnification imaging platform using $\lambda = 450$ nm light. This measurement technique requires a thorough understanding of the tool, rigorous electromagnetic modeling, as well as tailoring of the metrology target. This paper briefly reviews these recent accomplishments, target optimizations, and ongoing research into the challenges and extensibility of this scatterfield microscopy methodology.

QUANTITATIVE PARAMETRIC FITTING VIA IMAGING

Comparisons between experiment and simulation are made successfully in scatterometry for arrays of lines that are often larger than the incident spot size with pitches smaller than the wavelength. Much smaller line arrays (Fig. 1a) that would fit within the field-of-view of a microscope are desirable such targets will yield multiple scattering frequencies. These frequencies are inseparable within the real-space image, greatly complicating experiment-to-simulation comparisons. A new measurement approach has recently been published[1] that describes the fitting of simulation to experiment for intensity profiles obtained through-focus; two key components are highlighted here. First, the comparison is enhanced by correcting known errors from the instrument through Fourier Domain Normalization. When simulating the scattered field, the individual scattering frequencies are separable for each incident plane wave. By mapping the empirical imperfections of the tool through tool functions[2] (Fig. 1b), these known imperfections can be mapped upon each of the simulated, discretized Fourier components. By combining modified plane wave simulations to represent the finite aperture of the experiment, the resultant simulated image more closely takes on the imperfections of the experimental data.

Second, after investigating the possible Type "B" error components for the experimental data, potential error sources were determined to have correlated effects among the nominally independent measurements (the intensities at each pixel). These relationships were included within the covariance matrix (Fig. 1c) before performing the linear regression between simulated and experimental data to determine not only the best model parameter values but also their parametric uncertainties. Selected comparisons between Fourier Domain Normalized simulations and experimental profiles at several focus positions are shown in Fig. 1d.

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Paper presented at 2017 International Conference on Frontiers of Characterization and Metrology for Nanoelectronics, Monterey, CA. March 21, 2017 - March 23, 2017.

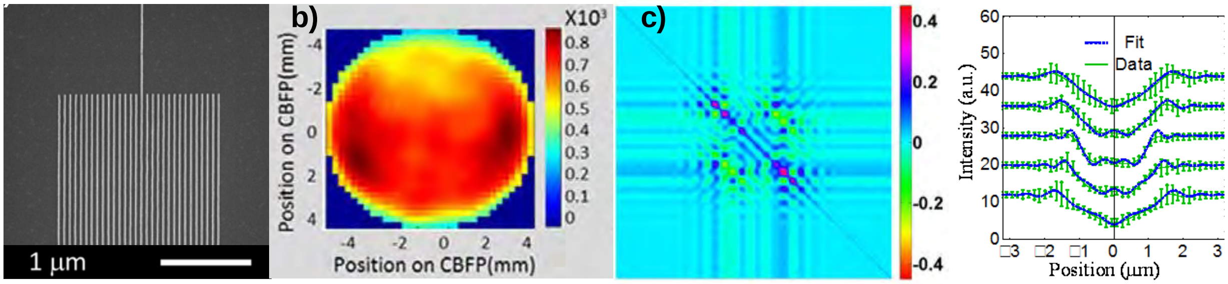

FIGURE 1. a) Scanning electron micrograph of a 30-line metrology target b) Example of an illumination path tool function (in arbitrary units) for one linear polarization. An aperture was rastered in the conjugate to the back focal plane (CBFP) of the objective lens and the light measured near the sample plane. Tool functions for the collection path were also required. c) Illustration of one part of an off-diagonal covariance matrix. d) Simplified example of theory to experiment fitting at five focus heights with multiple error bars removed for visual clarity. Actual fits were performed at 21 focus positions and two polarizations. Panels a), c) from Ref. 1, b) from Ref. 2.

OPTIMIZATION VIA SIMULATIONS

The metrology target in Fig. 1a has a patterned area of about 2 μm width and 6 μm length, excluding the protrusion for atomic force microscopy measurements. The total required area is also dependent upon the proximity of nearby objects, especially to the left and right of the target; objects should be at least 10 λ away from the sides of the target as shown in Fig. 2a. This observation is informed by simulations at $\lambda = 450$ nm for Ref. 1 of the target using rigorous coupled-wave analysis (RCWA), which implies a periodic structure. These 30-line targets were modeled as a repeating pattern of a finite set of lines surrounded by relatively vast unpatterned regions. The domain size was increased until the scattering from the target converged in amplitude, which occurred when the target was optically isolated from its periodic copies for a 10 μm domain. Simulations at 193 nm reinforce this 10 λ observation.

The specific target shown in Fig. 2a is impractically sized then for insertion into the active region of a device. Through simulation, however, optimization of the size and design of the target has been performed in addition analysis of the number of arrayed lines and number of focus measurements required to yield acceptable parametric uncertainties[3, 4]. The simulation study, unlike the fitting above, assumed a two-parameter model (height and mid-width) for simplicity and also application of a finite-element (FEM) Maxwell's equations solver to facilitate both two- and three-dimensional targets. It has been shown that using combinations of reduced line lengths and numbers of lines can potentially lead to a four-fold decrease in target area as compared to cutting-edge scatterometry targets[4]. In fact, as little as 10 lines can lead to uncertainties comparable to the ones obtained from measuring the larger 30-line target, see Fig. 2b. The restriction to less focus positions in the measurement can furthermore reduce the total time needed to acquire the necessary image data. Figure 2c shows little difference between taking images at four different focus positions and eleven focus positions. For favorable quantification of even smaller deep-subwavelength features, these optimization methods should be repeated to enable more thoughtful choices in geometrical layout and experimental design.

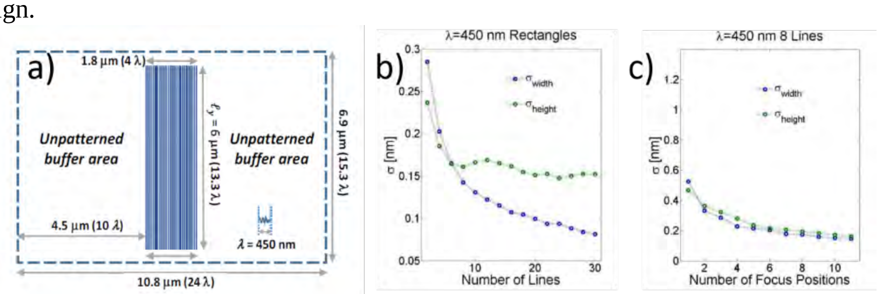

FIGURE 2. a) Initial proposed in-die target design (to scale) based upon the measured target from Ref. 1. The target has 30 lines with 60 nm pitch and line length (l_y) of 6 μm. A three-dimensional electromagnetic scattering model was used to determine the minimum line length for maintaining accuracy. b) Dependence of the estimated uncertainties on the number of lines. c) Dependence of the estimated uncertainties on the number of focus positions. Panel a) reprinted from Ref. 3.

CONSIDERATION OF POSSIBLE SYSTEMATIC BIASES

With increasing dependence upon accurate electromagnetic modeling for determining CDs, the limitations and simplifications assumed in these modeling methods become more relevant and may yield systematic biases in such measurement-to-model fits and yield erroneous parametric values. Two of the most prominent issues are the limitations due to the finiteness of the line arrays and the presence of roughness (Fig. 3a) in the measured targets. In order to reduce computation time and memory resources, arrays of lines are often assumed to be “infinite” along one spatial direction for modeling purposes, allowing the use of two-dimensional modeling codes. To test this assumption for the relatively short line lengths of proposed “in-die” targets, three-dimensional FEM-based simulations were compared against FEM-based two-dimensional solutions, shown in Fig. 3b. As shown, the simulated images diverge from the infinite model with decreasing line length, which if unchecked would lead to a systematic bias. The second source of systematic errors is the over-simplification of assuming perfectly smooth lines, whereas all actual arrays have some degree of line-edge width variation and roughness (LEWR). Simulation of such rough edges increases the computational challenges significantly, Fig. 3a shows an example of a rough grid used in simulations. The effect of the rough lines on the imaging can be observed in Figs 3c-d. A systematic bias that exceeds the expected random noise is introduced.

For both the finite vs. infinite comparison and the LEWR evaluation, two different ways to confront these problems are presented. The first one is to simply adapt the measurement set-up, i.e. choose measurement (including target) configurations for which the effects are minimal, while the second is to attempt to include resultant systematic biases into the actual modeling process.

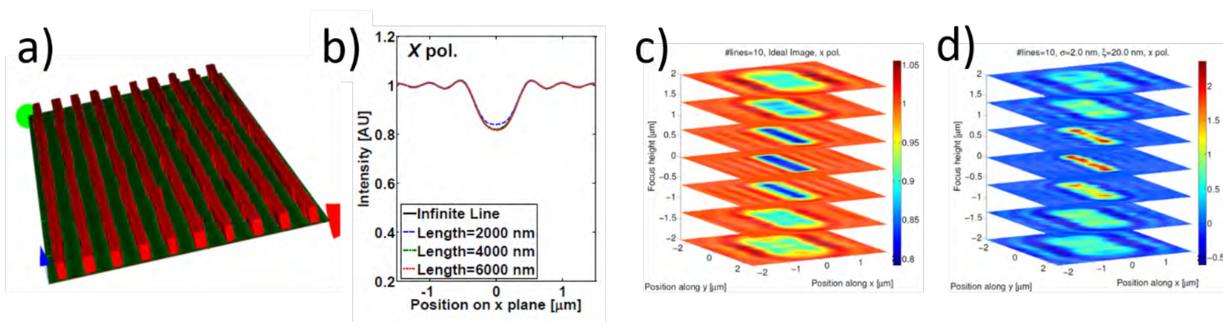

FIGURE 3. a) Single realization of a rough 10-line structure. b) Comparison between the profiles of the infinite and finite lines for three different line lengths l_y for a 10-line target at λ = 450 nm. c) Images of the ideal, i.e. non-perturbed 10-line structure at several focus positions. d) Relative difference between the image of ideal and rough 10 line structures at several focus positions.

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KEYWORDS

computational microscopy; light scattering; metrology; quantitative nanoscale microscopy; sub-nanometer uncertainties; metrology; scattering measurements; three-dimensional microscopy; linewidth; spatial frequency

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