Evaluating the Performance of a 193nm Hyper-NA Immersion Scanner Using Scatterometry

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ABSTRACT
Scatterometry techniques are used to characterize the CD uniformity, focus and dose control, as well as the image contrast of a hyper-NA immersion lithography scanner. Results indicate very good scanner control and stability of these parameters, as well as good precision and sensitivity of the metrology techniques.

Keywords: Immersion, hyper-NA lithography, Scatterometry, Focus and Dose monitoring, Scatterometry, PGFM

1. INTRODUCTION
With the transition of 65nm technology to production and the development of 45nm technology, lithography has become increasingly difficult. ITRS targets for the errors on the critical dimension of microprocessor gates are below 3 nm for the 45-nm node, with a corresponding budget for the metrology errors that is significantly smaller. In addition, the increased complexity of the lithographic processes and tighter error budgets demand more accurate metrology tools for the control of lithography clusters.

In this study, normal incidence optical critical dimension scatterometry (OCD) is evaluated as a technique for the precise characterization of advanced lithography scanners. In particular, we evaluate the performance of a 193-nm hyper-NA immersion scanner, the ASML XT:1700i, in terms of CD control, focus-dose uniformity, and image contrast.

2. SCATTEROMETRY BASICS
The scatterometry tool used for this study utilizes broadband polarized light incident normally to the surface of a wafer and analyzes the spectral content of the zeroth order diffracted light for the TE and TM polarization states. Figure 1 shows a typical set-up for such a system, which is termed normal-incidence optical critical dimension, or NI-OCD, metrology. There are specific advantages to using a normal incidence configuration. It allows a more compact footprint compared to non-normal incidence designs. CD profile information is determined by regression – i.e. first-principle rigorous coupled wave analysis (RCWA) is performed on resist-profile models to fit spectra from experiments. RCWA calculations are performed using Nanometrics’ ADAP (Advanced Data Analysis Package) software.
Sample TE and TM spectra for a grating with 60-nm lines on a 240-nm pitch are presented in figure 2. The agreement between the experimental and simulated spectra is excellent for the final structure inferred from the data.

To increase further our confidence in scatterometry-based CD metrology, we have used similar measurements and models to characterize the CD variation of a scanned image field from the XT:1700i and then compared the results with CD-SEM measurements. The bottom CD results for 60-nm lines on a 180-nm pitch are displayed in figure 3 below. It is to be noted that the variations observed across the image field are not representative of the performance of a well tuned scanner. These data were obtained prior to any adjustment and without subtracting the reticle contribution to the variation of CD. Rather, it is the excellent agreement of the CD-SEM and OCD results that is noteworthy. The difference plot of the across-field distribution in Fig. 3c is essentially flat and very close to zero, with an average offset of 1.2% of the CD. We also note that the CD-SEM results are significantly noisier than the OCD results. This is due mainly to the
fact that CD-SEM results are obtained from a single measurement per site while the scatterometry results are extracted from signal coming from many more lines and over a much larger area.

Fig. 3. Comparison of intrafield CD distribution. (a) OCD, (b) CD-SEM, and (c) difference.

3. MEASURING DOSE AND FOCUS

There are a number of reports in the literature about extracting focus and exposure conditions from the profile of features printed in resist.\textsuperscript{1-4} We will restrict our discussion of this technique to its basic principles, which are illustrated in figure 4. In general, the profile of a resist line can be characterized by measuring its top and bottom CDs (TCD & BCD). The dose used is related to the average CD and the focus condition is related to the slope of the line, or the difference between the top and bottom CDs. The model used for extracting focus and dose values is based on a polynomial fit of the Bossung curves for top and bottom CDs of lines printed in resist, using an optimized process for maximum sensitivity.\textsuperscript{5,6}

Fig. 4. A unique focus and dose can be obtained by monitoring at least 2 CDs (e.g. bottom and top CD) of a resist line. As an example, two solutions for focus exist ($f_a$ and $f_b$) if only the bottom CD (BCD) is measured. However, measuring the top CD allows to predict a unique solution for focus ($f_a$).

The process used for the scatterometry-based focus and dose metrology (SFDM) is based on printing 60-nm lines on a 240-nm pitch. The model fits to the experimental Bossung curves are shown in figure 5, along with correlation plots of the model-predicted and commanded values of focus and dose. The fits and correlations are excellent, providing a self-consistent verification of the technique.
Fig. 5. Figures (a) and (b) show field-averaged BCD and TCD Bossung curves. Focus is programmed in 25nm steps and exposure dose is programmed in 1mJ/cm$^2$ steps. Figures (c) and (d) shows excellent correlation ($R^2=0.984$ for BCD model and $R^2=0.984$ for TCD model) between the commanded values and those predicted by the SFDM model.

Next, we conducted an experimental comparison of this SFDM technique with the phase-grating focus monitoring (PGFM) technique, on which we rely for our most critical focus evaluation needs. Wafers were printed with an array of focus and exposure dose conditions, also known as a focus-exposure matrix (FEM), and we extracted focus values from the SFDM and the PGFM techniques.$^{7,8}$ A correlation plot of results based on the two techniques appears in figure 6. The correlation is extremely good ($R^2>99\%$) and indicates that SFDM should be a useful tool for characterizing focus control of lithography tools and processes.
4. SCANNER CHARACTERIZATION

4.1 Comparison of PGFM- and SFDM-based characterization of focus control

Across-wafer focus control was evaluated both with SFDM and PGFM. For the SFDM technique, OCD measurements were performed on both horizontal and vertical gratings at 16 sites per field, for the whole wafer. Figure 7a shows the across-wafer focus variations and histogram of focus variations for the same data. In addition, SFDM can be used to extract exposure dose information and the wafer map of the dose uniformity is presented in figure 7b. We find that the focus distribution has a standard deviation of 8.1 nm and the dose distribution is characterized by $\sigma = 0.34$ mJ/cm$^2$. For comparison, the PGFM results, which are based on a much denser sampling of 221 points per field, are displayed in figure 8. The standard deviation of the PGFM focus distribution across the wafer is higher ($\sigma = 12.6$ nm) than that of the SFDM results but it includes data at the edge of the wafer, which broadens the distribution due to the wafer bevel.
Fig. 7. Across-wafer focus and dose distribution as measured with scatterometry (SFDM).

Fig. 8. Across-wafer focus distribution as measured with phase-grating focus monitor (PGFM).
4.2 CD uniformity and stability

In this section we report on the CD control of the 1700i scanner, based on the scatterometry metrology. The experiment was carried out over a period of a full week (7 days) and data were collected on three different days during this period. Bottom CD values were extracted from scatterometry measurements of 60-nm resist lines on 180-nm pitch. The results indicate a very uniform distribution across the wafer ($σ~4.5$ nm) and a very stable behavior. Careful inspection of these wafer maps reveals that there might still be some systematic errors within the scanned field and across the wafer. This can be inferred from the fact that one can identify boundaries between adjacent fields on the wafer and also from the existence of a three-fold symmetry across most wafers. These systematic errors might be correctible through a revised scanner set-up procedure and lead to CD uniformity numbers below 0.7 nm rms.

![Wafer maps with iso-CD contours](image)

The long-term CD control can be characterized by the CD variability across wafers for an extended period of time. For the 7-day period over which we ran our experiment, the average CD uniformity across wafers was 4.5 nm and varied by about 0.6 nm in the direction of either smaller or larger CD.
4.3 Modulation transfer function (MTF) metrology

The modulation transfer of a lens is a useful metric to evaluate its quality. For lithography applications, the modulation transfer function, or more accurately the contrast curve, measured in resist also provides information about the lens quality\(^9,10\) but also about the resolution of the resist process used\(^11\). Such contrast curves can be obtained by determining at which exposure dose gratings of different pitches start to print (D1) and then disappear completely (D2), as is schematically illustrated in figure 11. The contrast value for any given pitch is then calculated as:

\[
MTF\left(\frac{1}{p}\right) = \text{contrast}(p) = \frac{D_2(p)/D_1(p) - 1}{D_2(p)/D_1(p) + 1}
\]

As reported in an earlier paper\(^10\), the repeatability of such measurements is usually affected by large uncertainties due to human assessment of the dose values at which the grating lines appear and disappear.

To address this repeatability problem, we have developed an automated technique for measuring the contrast curve of a scanner based on scatterometry, which provides unique start- and end-point detection for determining D1 and D2 more systematically. A sample application of this technique consists in measuring the contrast curves for two different polarized illumination cases. The results obtained for X- and Y-polarized light on a 1.2NA immersion tool, with conventional illumination (\(\sigma=0.93\)), are displayed in figure 12. On this graph, the measured contrast is plotted as a...
function of the normalized spatial frequency, which is defined as $\text{nsf} = \lambda / (2 \text{NA} \cdot p)$, where $\lambda$ represents the wavelength, NA is the numerical aperture of the scanner, and $p$ is the pitch of the grating. The measurements clearly confirm the better image contrast for small pitches (larger spatial frequencies) when Y-polarized light is used. This is the case corresponding to TE-polarized illumination ($E$ field aligned to the lines of the grating). The experimental results agree very well with aerial image simulations using a pupil of $\sigma = 0.85$, and a Gaussian blur of $\sigma = 20$ nm (e.g., due to the diffusion-deprotection reactions in the resist). The discrepancy between the value of pupil fill used in the simulation to fit the experimental results and that used on the scanner might be due to a difference in the definition of $\sigma$.

![Contrast curves of the XT:1700i for X- and Y-polarized light.](image)

*Fig. 12. Contrast curves of the XT:1700i for X- and Y-polarized light. The circular symbols denote the experimental results obtained with NA=1.2 and $\sigma = 0.93$, while the dashed curves represent the simulated contrast using the following parameters: NA=1.2, $\sigma = 0.85$, and a Gaussian blur of 20 nm (1$\sigma$).*

5. **CONCLUSIONS**

We have used scatterometry techniques to characterize the performance of the ASML XT:1700i lithography scanner in terms of CD uniformity and stability, focus and dose control, and image contrast. The scatterometry results were compared to other well-established techniques such as CD-SEM and phase-grating focus monitors, as well as to aerial image simulations, and very good agreement was obtained.

The XT:1700i hyper-NA immersion scanner performed well with CD uniformity across the wafer of less than 5 nm (6$\sigma$), focus control of 50 nm to 75 nm (6$\sigma$) over the full wafer, and very good image contrast using polarization control.

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