In-line focus monitoring and fast determination of best focus using scatterometry

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ABSTRACT

Persistently shrinking design rules and increasing process complexity require tight control and monitoring of the exposure tool parameters [1, 2]. While control of exposure dose by means of resist single metric measurements is common and widely adopted. Focus assessment and monitoring are usually more difficult to achieve. A diffused method to determine process specific dose and focus conditions is based on plotting Bossung curves from single CD-SEM measurements and choosing the best focus setting to obtain the desired target CD with the widest useful window. With this approach there is no opportunity to build a data flow architecture that can enable continuous focus monitoring on nominal production wafers [3-5]. KLA-Tencor has developed a method to enable in-line monitoring of scanner focus on production wafers by measuring resist profile shapes on grating targets using scatterometry, and analyzing the information using AcuShape™ and K-T Analyzer™ software. This methodology is based on a fast and robust determination of best scanner focus by analyzing focus-exposure matrices (FEMs). This paper will demonstrate the KT CDFE and FEM Analysis methods and their application in production environment.

Keywords: focus, process control, lithography

1. INTRODUCTION

The merits of hyper Numerical Aperture (NA) imaging using 193nm exposure wavelength with water immersion since 75nm nodes have been demonstrated widely by the semiconductor industry. The same industry is driven by ground rule shrinks thereby reducing manufacturing cost and improving device performance. The non-readiness of Extreme Ultra Violet (EUV) lithography has forced manufacturers to continue to settle for 193 immersion tools with NA \( \approx 1.35 \). Moving to sub-32nm nodes, NA scaling has become more of a threat than a viable solution; therefore, aggressive \( k_1 \)-scaling has been explored with a large set of approaches including Resolution Enhancement Technology (RET) such as Optical Proximity Correction (OPC), Source/Mask Optimization and others, in addition to a heterogeneous landscape of pattern split/duplication integrated process flows. All of these factors have led to a drastic shrink of useful process windows which imply imposing extremely tight requirements on parameters such as critical dimension uniformity (CDU). Nevertheless all of these workarounds have generated a stall in the sensitivity of process monitor gratings at design rule, which have started to show almost flat response to defocus modulations and sudden window reductions associated with pattern roughness increase or profile changes and pattern collapse. As low \( k_1 \) imaging processes are generally more sensitive to process variations, a critical area for successful process parameters optimization is seen in the wafer level effective defocus and dose fluctuations characterization and control. Therefore real-time monitoring capability to detect local focus and exposure conditions on production wafers becomes necessary.

The usage of Scatterometry Critical Dimension (SCD) metrology based on spectroscopic scatterometry has shown to provide numerous benefits spanning from an excellent repeatability in the determination of physical properties of patterned structure profile which is not limited to CD only, to unmatched measurement throughput (typically less than 2 seconds per measurement) which enables high rate sampling. These factors are aligned with the actual need of production lines for a quick and easy determination of on-product best focus and in line wafers focus and dose error.
determination. In this paper we will concentrate on the determination of best scanner focus and on-product focus monitoring using 28nm product wafers by utilizing a fully-automated solution suitable for high volume manufacturing.

2. SCATTEROMETRY MEASUREMENTS

Scatterometry measurements require target structures that are periodic in nature. While it is possible, in principle, to measure the device patterns themselves, provided those are repeating over the measurement spot, it is common to use simple line/space proxy targets for easier model setup. In contrast to previous publications [6],[7], which describe the use of specifically designed isolated structures to extract focus information, this work utilizes dense grating targets at critical design rule dimensions. For the process this work is based on, dense gratings are being used for dose control and thus do exist in the layout already, so no additional GDS design was required. Further, dense gratings are more likely to behave similar to the device, which leads to more representative measurement results. Grating targets at design rule are already widely used in the industry for CD-SEM and scatterometry-based metrology, therefore a consistent reference baseline for the CD parameters already exists and represents the fundamental link to the final successful assessment of a proper patterning process. Another advantage of applying the metrology effort on design rule targets is the absence of potential cross-talk between coma aberration and shape of the target itself which would definitely end up into inaccurate focus latitude assessment.

To achieve robust measurements, and to deconvolve lithography from process information, the scatterometry signal is taken from two different structures. First, film thicknesses of process layers underneath the grating are measured on an unpatterned film stack pad. Second, the results of the first step are fed forward while measuring the actual grating target. The advantages and benefits of this approach have been discussed previously [7].

![Figure 1: Feed forward of films and grating measurement (schematic cross section)](image)

For the experiments described, scatterometry measurements have been taken on two different front end layers in the 28nm logic process, with different process layers underneath and slightly different dense resist gratings. This same approach was previously verified as a learning cycle on a 32nm logic process as foundational work toward the work reported in this paper.

3. METHODOLOGY OF FOCUS MONITORING

The method used in this work utilizes an Archer™ 300 LCM scatterometry measurement tool, the AcuShape modeling software and the K-T Analyzer analysis package. The procedure is comprised of the following steps:

- Using the AcuShape software, build a model to extract resist profile geometry (such as line width, profile height and side wall angle) from measurements taken from the scatterometry tool
- Process a focus exposure matrix (FEM) wafer and build a model to describe the relationship between focus and dose
- Apply this model to scatterometry measurements taken on production wafers to calculate focus and dose information from resist profile parameters

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A schematic illustration for the focus monitoring is depicted in Figure 2.

A detailed description of those components was provided in a previous publication [6].

4. FOCUS MONITORING EXPERIMENTAL RESULTS

In order to verify the accuracy of the approach described above, a set of six wafers (5 positions) was exposed as illustrated in Figure 3. Each wafer was processed with nominal exposure conditions, but with intended focus offsets in steps of 15nm from wafer to wafer. Essentially, this experiment is an attempt to represent scanner focus drift over time.

Figure 3: Focus monitor test wafers

Figure 4 shows the comparison of the designed and the measured focus offset as average focus value per wafer, and Table 1 summarizes the results. It can be seen that the evaluated methodology is able to report wafer-to-wafer focus variations quite accurately.

It shall be noted that only one grating target per exposure field was available on these wafers, therefore neither intra-field signatures could be evaluated nor field averaging could be performed. Previous studies have shown intra-field focus variations larger than 20nm [7].
Figure 4: Layer A and B focus monitor correlation plots

<table>
<thead>
<tr>
<th>Layer</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope</td>
<td>0.831</td>
<td>1.190</td>
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<tr>
<td>Intercept</td>
<td>-1.756</td>
<td>-6.835</td>
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<tr>
<td>R²</td>
<td>0.988</td>
<td>0.949</td>
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<tr>
<td>RMSE</td>
<td>4.9</td>
<td>7.8</td>
</tr>
</tbody>
</table>

Table 1: Layer A and B focus monitor simulation results

Figure 5 shows sample data of in-line focus monitoring of the above-mentioned layer A. The Y-Axis shows the lot average of measured focus, and the x-axis is time. Note that data from multiple exposure tools is included in this graph.

Figure 5
5. METHODOLOGY OF BEST FOCUS CALCULATION

Currently, scanner best focus is commonly determined using CD-SEM measurements. As different device patterns react differently to focus and dose, optimal exposure conditions need to be found and validated on multiple structures using a CD-SEM which is relatively slow. The entire procedure can become quite time consuming; several hours are usually required to obtain results. Furthermore, the actual determination of best focus is, to a certain extent, a manual process which potentially leads to dangerous user-to-user variations of the final results.

In contrast, the method described herein is an automated process devoid of user interaction, and is executed using scatterometry measurements which are significantly faster than those from a CD SEM.

For the determination of scanner best focus, the process window capabilities of the K-T Analyzer software are leveraged. The same grating targets and measurement approaches as described in Section 2 are employed. Listed below are the steps required to obtain the necessary data:

- Extract the resist profile parameters using the same AcuShape model as in section 2
- For each of the parameters (width, height, angle), define the allowable range (process window). Such ranges for height and side wall angle, in particular for resist, may not be known beforehand. If that is the case, initial reference measurements, e.g. from CD-SEM, are required to assess the process window for each parameter.
- Read the scanner’s best focus as the center of the overlapping process windows

![Figure 6: Overlapping process window principle](image)

6. BEST FOCUS EXPERIMENTAL RESULTS

A similar set of five wafers as was used in section 4 was exposed (Figure 7). All five wafers were processed as focus exposure matrices (using 15nm focus increments from wafer to wafer) while centering each wafer on a different nominal focus value.
The same two front end layers as in the previous experiment were evaluated. The results of this experiment are shown below in Figure 8 and Table 2.

<table>
<thead>
<tr>
<th>Layer</th>
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<th>B</th>
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<tbody>
<tr>
<td>Slope</td>
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<tr>
<td>Intercept</td>
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<td>-6.259</td>
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<tr>
<td>R²</td>
<td>0.970</td>
<td>0.964</td>
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<tr>
<td>RMSE</td>
<td>11.7</td>
<td>7.3</td>
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</tbody>
</table>

Table 2: Layer A and B best focus results

7. CONCLUSIONS AND FUTURE WORK

Based on experimental data, it was shown that the Archer 300 LCM and K-T Analyzer solution is suitable for focus monitor and best focus applications in a 28nm process. It has been shown as well that a suitable way for running product best focus assessment and focus monitor is viable using existing conventional gratings at the critical design rule without the need for specific target design optimization and subsequent mask tape-out iterations. For focus monitoring, it was demonstrated that a possible focus drift can be detected at an error level of approximately 5 to 8nm (RMSE). Scatterometry technology is an enabler for this use case, as commonly used CD-SEM tools neither provide enough information from the resist profile, nor fulfill the tight throughput requirements for in-line measurements at higher sampling rates. Similarly, best focus can be determined at an error level of 7 to 12nm at a higher level of confidence, less user-to-user variability and shortened time-to-results, the latter again due to the extremely high throughput advantage of scatterometry technology.
For future usage and implementation, multiple grating targets per exposure field should be considered, first to assess intra-field signatures, and second, to gain higher statistical confidence.

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REFERENCES