High Throughput Grating Qualification for Rating Directed Self-Assembly Pattern Performance using Optical Metrology

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This paper describes a novel scatterometry-based optical inspection technique to quantify the degree of ordering of line/space gratings fabricated through a chemo-epitaxy directed self-assembly process. Process window analysis with this optical metrology is compared to analysis based on SEM and excellent agreement is demonstrated. However, other process parameters, including pattern CD, profile and especially pattern height influence the output signal. This requires normalization to a known good condition for correct data interpretation. The optical technique is useful for evaluating performance of closely related processes, and is thus ideally suited for bake optimizations, material selections, and monitoring purposes.

Keywords: directed self-assembly, line/space patterns, chemo-epitaxy, metrology

1. Introduction

Directed self-assembly (DSA) of block copolymers (BCP) is receiving increased attention for use in future semi-conductor manufacturing. As a bottom-up patterning technique it may be used for pattern rectification such as contact hole shape repair [1], critical dimension (CD) uniformity repair [2] or line width roughness (LWR) repair [3]. In other approaches, DSA may be applied as a resolution enhancement technique to achieve frequency multiplication. Experimental demonstration of frequency multiplication for hexagonal hole patterns [4], as well as line-space patterns [5, 6] have been reported.

In traditional top-down optical lithography, the pattern CD is most commonly used as figure of merit for setting up and optimizing a process. Process windows are typically defined by the amount of CD variation that is induced by variation of exposure setting such as dose and focus [7]. In DSA this approach is not so useful, since CD of the resulting patterns is mainly determined by the intrinsic molecular length of the BCP. In contrast, the ‘degree of alignment’ of the self-assembled patterns to the guide structures is a better metric to define the process window.

Figure 1. Top-down SEM images of perfectly aligned (left), partially aligned (middle), and unaligned (right) BCP structures upon chemo-epitaxy DSA.

Top-down CD SEM measurements are able to provide this type of information (Figure 1), but suffer from two drawbacks: 1) the field of view (FOV) of an SEM image is limited; in order to properly judge a certain process condition multiple images at low magnification need to be collected, and 2) on commercially available automated CD
SEM there is no image processing software available to evaluate the degree of alignment, thus manual image processing is required.

In this paper we present an optical scatterometer-based metrology technique to quantify the degree of alignment of line/space patterns formed by a chemo-epitaxy DSA process. This technique has the advantage of measuring with a large spot size (and thus collecting more statistical information than with the SEM) and fast data processing capabilities. The performance of the technique for screening process and material optimization will be determined and the results will be anchored to SEM analysis.

2. Experimental Details

2.1 DSA pattern fabrication

Details of the chemo-epitaxy DSA flow (Figure 2) to fabricate 28nm pitch line/space patterns from an 84nm pre-pattern (3X frequency multiplication) have been presented previously [8]. Briefly, cross-linkable polystyrene (AZEMBLY™ NLD-128, AZ Electronic Materials) is coated on a 300mm silicon wafer with 14nm SiNx and annealed. The 84nm pitch pre-pattern is exposed as a focus-exposure matrix (FEM) in AIM5484 photoresist from JSR Micro using 193nm immersion lithography. An oxygen-based etch chemistry is used to trim the resist to the target CD (~18nm) and to break through the polystyrene mat. Next, the photoresist is selectively removed in a wet strip process. After this, -OH terminated random polystyrene/PMMA copolymer (AZEMBLY™ NLD-127) is coated and annealed. During this annealing step the polymer brush selectively grafts to the exposed nitride substrate, but not to the cross-linkable polystyrene (XPS). Excess brush material is removed by a solvent rinse to yield the chemical pre-patterns. Finally the BCP material (AZEMBLY™ PME-312) is coated, annealed for 5min at 250°C and the PMMA block is removed by a dry etch process to yield a 14nm half pitch polystyrene line/space pattern.

In part of the work described in this paper, a 90nm pitch pre-pattern and a 30nm L0 BCP material was used. Otherwise, similar process conditions were applied as described for the 28nm L0 material described above.

2.2 Metrology

A Hitachi CG4000 top-down CD SEM was used for all SEM analysis. For process window qualification, typically 10 images per die at low magnification (50kX) were collected at different locations in the inspection block to yield a total inspected area of ~70 µm². On a full wafer this process requires 2hrs of SEM tool time and 2 hrs of manual data processing.

For the optical inspections an ASML YieldStar™ S-200 tool, an angle-resolved polarized reflectometry based scatterometer with ~30 µm spot diameter was used (inspected area ~700 µm²). In all cases single wavelength analysis at 425nm was carried out. The metrology output was analyzed with a proprietary method, yielding a single quality number (score) per inspection. The same analysis with this method as described above for SEM inspection requires 4min of tool time and 6min of data processing.

3. Results and Discussion

3.1 Comparison of optical metrology to SEM

A first assessment of the potential of the optical metrology technique is made by examining the response through exposure dose of the pre-patterns...
Figure 3. Optical metrology score as a function of exposure dose of the pre-pattern for 2 wafers that were processed under different conditions. Representative SEM images are given for selected exposure doses.

(Figure 3). As exposure dose increases the width of the XPS guide stripes decreases. When the width becomes too small, it is known that this will lead to a loss of guidance of the BCP by the pre-patterns, resulting in (partially) unaligned patterns [9, 10].

On a first wafer, the score (in arbitrary units) from the optical metrology is constant over a window that matches well with the exposure doses over which perfect alignment is also observed in the SEM. When the score from the optical technique drops, this coincides with partial alignment found from SEM inspection. This result provides a first indication that the optical technique is capable of scoring the degree of BCP alignment. Inspection of a second wafer (which was processed under different conditions) shows a similar result, but the absolute score of the optical technique is significantly lower in this case. Especially noteworthy is the point at which the score of wafer 1 starts to drop. The absolute score of this data point on wafer 1 is higher than the maximum score on wafer 2. Nevertheless, this location corresponds to partial alignment on wafer 1, whereas on wafer 2 perfect alignment is found over the entire window that gives the maximum score. It is thus concluded that the absolute score is meaningless, but first needs to be normalized to a known good location that is processed under identical conditions. In the remainder of this work such normalization will be done by dividing the individual score per location on the wafer with the maximum score on that wafer. Naturally, this approach requires SEM verification of that maximum score to ensure that this location indeed does correspond to perfect BCP alignment.

Separately, tests have been run to confirm that the signal from the optical metrology technique indeed comes from the BCP structures and not from the underlying pre-pattern. This has been done by running the metrology method on pre-pattern wafers without BCP material (only the chemical patterns). Also, comparison of the score in off-target pre-pattern areas, resulting in fully random BCP orientation with the score in non-patterned areas (‘fingerprint patterns’) indicates that the optical signal stems almost exclusively from the BCP patterns.

3.2 Effect of BCP film thickness

In a next step the impact of BCP film thickness on the DSA process was studied. The pre-patterns in this are all prepared using identical process conditions and the spin speed that is used for casting the BCP layer is the only process variable.
From separate work using SEM analysis it was seen that the process window of the DSA process increases monotonically as the BCP film thickness is reduced. In contrast the maximum score per wafer of the optical metrology technique increases monotonically with film thickness (Figure 4, top). Apparently, the score is strongly dependent on pattern height. From the SEM-based process window analysis it was known that each wafer had at least one die that displayed perfect BCP alignment on the pre-patterns. Normalization as of the optical grating qualification scores described in the previous section results in a similar trend as was observed with SEM-based analysis. The average normalized score over the entire wafer drops monotonically as the film thickness is increased (Figure 4, bottom), representing the reduction in DSA process window.

3.3 Effect of neutral layer composition

The impact of neutral layer composition has also been studied by the optical metrology technique. Six formulations (A-F) of the neutral brush were available where the relative polystyrene content in the composition was systematically increased from low (A) to high (F). These samples were analyzed based on their process windows as determined from top-down SEM analysis (Figure 5).

![Figure 4. Maximum value of the absolute score of the optical metrology technique increases with BCP film thicknesses (top). Wafer average of the normalized score shows that the process window reduces with increasing BCP thickness (bottom).](image)

![Figure 5. Comparison of process windows as determined from FEM wafer maps for brush formulation A-F. Wafer map of SEM based measurements is each time give on top and of optical metrology on the bottom. The white lines in the SEM-based wafer maps indicate the area of defect-free alignment. The colors of the optical wafer maps use identical scales for coloring. The bar graph indicates the normalized full wafer average of all optical scores and is indicative of the process window.](image)
showed a significantly reduced process window for BCP alignment and formulations E and F did not show any condition for defect-free alignment. For this reason the average of the maximum score of formulations A-D was used for normalization of the optical measurements on formulations E and F. Since the pattern height appears to be the most dominant (but not the only) parameter that influences the absolute optical score, this approach seems reasonable, as the BCP material, thickness and processing are all identical within this set of experiments.

Figure 5 demonstrates that the reduction in process window as found from the SEM analysis is also seen from the optical inspection results. The wafer maps for formulations A-C are similar for both the SEM and the optical metrology. Formulation D also shows the reduced process window from the optical result and the magnitude of the maximum is clearly reduced for formulations E and F.

3.4 Effect of BCP composition and pre-pattern pitch

Finally, four different 30nm $L_0$ BCP formulations were tested, all at closely matched film thickness. In a separate experiment the $L_0$ of the BCP materials was determined from Fast Fourier Transform analysis of fingerprint patterns that were obtained by spin-coating the BCP material on neutral layer and annealing. The results showed that all formulations met the 30nm $L_0$ target within 0.5nm. The materials were tested at the commensurate target pitch of the pre-pattern (90nm) and at various pitches around it. In this case the analysis was not done based on the full process window, but on different target structures at best dose and focus for the pre-pattern structures (Figure 6).

The results show that the response of the different BCP formulations to the pre-pattern pitch is different. As the pre-pattern pitch is increased from 90nm, BCP1 already shows reduction of the optical score at 91nm pitch. BCP3 not only starts to reduce at pitch 93nm, but also maintains a higher score than the other formulations. When reducing the pitch from the 90nm target, a less dramatic effect is seen. This is in line with previous observations, that indicate that the BCP materials are more forgiving when being compressed at pre-pattern pitches just below the commensurate pitch, than when being stretched at pre-pattern pitches above it.

The results from the optical inspections are also well in agreement with those of SEM-based inspections where it was found that BCP3 is the most stable material towards process variations and BCP1 is least forgiving.

4. Conclusions

In this paper we presented an optical scatterometer-based metrology technique to quantify the degree of alignment of line/space patterns formed by a chemo-epitaxy DSA process. In contrast to regular scatterometry, this technique requires no model setup or information on the optical properties of the employed materials. It is fast and thus is well-suited for screening during process and material optimization. The absolute score that is provided by the technique does however not only contain information on the pattern order, but is convoluted with other pattern parameters, the most important of which being pattern height. For proper interpretation, normalization to a known good location on the wafer is required.

When this method is properly followed, excellent agreement between the optical metrology process window results and top-down SEM results is obtained.
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