Effect of partial coherence on dimensional measurement sensitivity for DUV scatterfield imaging microscopy

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Abstract: Optical scatterfield imaging microscopy technique which has the capability of controlling scattered fields in the imaging mode is useful for quantitative nanoscale dimensional metrology that yields precise characterization of nanoscale features for semiconductor device manufacturing process control. To increase the sensitivity in the metrology using this method, it is required to optimize illumination and collection optics that enhance scatterfield signals from the nanoscale targets. Partial coherence of the optical imaging system is used not only for enhancing image quality in the traditional microscopy or lithography but also for increasing the sensitivity of the scatterfield imaging microscopy. This paper presents an empirical investigation of the effect of partial coherence on measurement sensitivity using a deep ultraviolet scatterfield imaging microscope platform that uses a 193 nm excimer laser as a source and a conjugate back focal plane as a unit for controlling partial coherence. Dimensional measurement sensitivity is assessed through analyzing scatterfield images measured at the edge area of periodic multiline structures with nominal linewidths ranging 44-80 nm on a Molybdenum Silicide (MoSi) photomask. Intensities scattered from the targets under the illuminations with various partial coherence factors and two orthogonal polarizations are assessed with respect to sensitivity coefficient. The optimization of partial coherence factor for the target dimension is discussed through the sensitivity coefficient maps.

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1. Introduction

The next generation computing devices that evolve towards mobile-oriented, cloud-based, and high speed-driven network environments require manufacturing of ever-decreasing features to meet the demands of advanced technologies including integrated circuits based on advanced transistors logic gates and quantum computing devices based on qubit logic gates [1–3]. Dimensional metrology for characterization of these nanoscale features occupies an essential place in the manufacturing process of those nanoscale devices [4,5]. Optical dimension measurement methods have unique benefits of nondestructive character, higher measurement speed, and relatively lower cost, comparing to other major measurement methods such as scanning electron microscopy (SEM) or atomic force microscopy (AFM) [6,7]. As the critical dimension (CD) approaches to deep sub-wavelength sizes which are deeply beyond the resolution limit, optical metrology has been transitioning from image-based microscopy to scatterometry-based microscopy using the model-based metrology that matches measured scattered intensity profiles to the modeling [8–10]. A key challenge of this scatterometry-based metrology is the accurate dimensional measurement for nanoscale features, which requires high measurement sensitivity with low uncertainty as well as high throughput [12–14].

Scatterfield imaging microscopy technique, which combines imaging microscopy and scatterometry, enables accurate dimensional measurements of periodic nanostructures sized deeply below the resolution limit with low uncertainty by controlling the illumination to tailor scattered fields and analyzing the far field image scattered at the target [15-18]. In the technique, the accurate and reliable measurement for the target characterization depends strongly on the illumination condition [19]. Quantitative CD measurement for finite multilines with sub-20 nm linewidths using a visible light scatterfield imaging microscope was reported showing the parametric regression matched between the simulation and experiment with sub-nanometer uncertainties [20]. In the experiment, it was noticed that a partially coherent illumination with low numerical aperture (NA) triggered obvious ringing artifacts at the edge of the intensity profiles, which might be related to the measurement sensitivity. To investigate the relationship of the illumination to the sensitivity, a series of measurements for multilines on a Molybdenum Silicide (MoSi) photomask were performed upon various illuminations augmented with incident beam shape, partial coherence factor, and polarization using a 193 nm scatterfield imaging microscope [21]. The results showed that the partial coherence has a significant impact on the improvement of the sensitivity for the dimensional metrology based on the scatterfield imaging microscopy, by altering the scattered field distributions. The primitive evidence of the impact of partial coherence necessitates further investigation over a broad range of target dimensions with a quantitative analysis for the accurate illumination optimization.

This paper presents an empirical analysis of the partial coherence effect on the measurement sensitivity for the multilines ranging 44–80 nm using a deep ultraviolet (DUV) scatterfield imaging microscope operating with a 193 nm excimer laser. First, the measurement principle of the scatterfield imaging microscopy and the experimentation for the illumination engineering to manipulate the partial coherence factor using a 193 nm reflection scatterfield imaging microscope are described with detailed parameters. Then, the experimental results concerning scattered intensity response and sensitivity coefficient over the target linewidth range are presented and discussed to provide the optimal illumination conditions.

2. Effect of partial coherence on scatterfield imaging microscopy

The degree of partial coherence significantly affects the image quality and resolution in high resolution imaging microscopy and reduction photolithography systems, since the optical transfer function and its passband of spatial frequency rely on the coherence of the optical systems [22–25]. The partial coherence factor σ signifies the degree of coherence of an optical imaging system, which is defined as $\sigma = NA_{ill} / NA_{col}$, where NA_{ill} and NA_{col} are for the illumination and collection beams, respectively [26,27]. It is noted that the partial coherence in optical microscopy is adjustable by varying the NA of the illumination light and must be optimized to yield desired image quality for diverse applications. To the definition of the partial coherence factor, lower σ indicates higher coherence, which is obtained with low illumination NA in the optical imaging system. For reduction photolithography and high-resolution imaging microscopy, the partial coherence factor is traded off between the imaging resolution and the edge ringing artifacts to yield the optimized image sharpness [28–31].

Exploiting the partial coherence has a different impact when it is applied to the scatterfield imaging microscopy for model-based nanoscale dimensional metrology in which the resolution reaches beyond the diffraction limit and the measurement sensitivity becomes the essential factor [21]. Figure 1 depicts the partial coherence effects on the measurement sensitivity in the scatterfield imaging microscopy by comparing the scattered intensity profile variations at the edges between two kinds of samples, a simple step and multilines with varied linewidths. Typical step edge intensity profiles in Fig. 1(a) shows that the lower partial coherence factor (σ_1) implemented with lower illumination NA exerts the intense ringing artifact with overshoot due to the higher coherence. Though the magnitude of the ringing and overshoot depends on the



partial coherence factor σ_n , the intensity heights are maintained at the same level regardless of the coherence degree.



Fig. 1. Schematic of the edge-scattered intensity profiles for partial coherence factor variations with respect to two kinds of targets: (a) a simple step, showing edge response with overshooting and ringing as a function of partial coherent factor (b) multilines with three different linewidths, showing varied intensity level for two degrees of partial coherence factor.

On the other hand, the scattered intensity profiles for the periodic multiline targets beyond the optical resolution limit appears different from the step edge. In Fig. 1(b), the upper and lower graphs show the intensity variations for the multiline set with three different linewidths, L_1 , L_2 , and L_3 . The intensity height difference between the linewidths for the lower partial coherence factor σ_1 in the upper graph appears bigger than for the higher partial coherence factor σ_2 in the lower graph. Consequently, the intensity height change signifying the sensitivity for the linewidth change depends on the partial coherence factor. The intensity profile around the edge is affected by the scattered lights at both edge and multiline area as a function augmented with both the partial coherence factor and the multiline parameter such as linewidth and height. The steepness and ringing artifact are changed by edge scattering, whereas the intensity heights are varied by multiline scattering. The two scattering effects are combined in the signals at the boundary area of the multiline parameters, allowing the characterization of nanostructure including critical dimensions and defects in periodic nanostructures. Optimizing the degree of coherence for specific linewidth variation yields high measurement sensitivity.

3. Experimentation

The experimentation for DUV scatterfield imaging microscopy is implemented with three main parts: construction of the optical paths, manipulation of the partial coherence factor, and measurements for the nanoscale multiline targets. The experimental environment is designed to be in a class 10 cleanroom to avoid the contamination of the nanoscale targets and the enclosed optical paths filled with nitrogen gas due to possible damage on the lens coatings caused by the ozone generated with a 193 nm Excimer laser light.

To construct the efficient microscope optical paths for 193 nm wavelength, an illumination optics based on double telecentricity and a collection optics with a high magnification were

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designed and optimized with respect to a catadioptric objective lens using an optical design software, OpticStudio of Zemax, for the manipulation of illumination beam shape at the sample, which alters the scattered light, as shown in Fig. 2(a) [32]. The actual microscope platform is constructed with a set of custom-made lenses in accordance with the design as shown in Fig. 2(b). An ArF Excimer laser of 193.3 nm wavelength which is widely employed for contemporary DUV lithography is used as the light source. The rectangularly collimated beam emerged from the laser is converted to the circular beam through a beam shaping optics with cylindrical lenses and a circular aperture. The converted beam becomes the divergent source (S) at a rotating diffuser with a low diffusing angle, which is mounted on a local isolation plate to avoid the vibration effect transferred to the scatterfield image through the optical table. The illumination NA and shape at the sample are controlled at the conjugate back focal plane (CBFP) of the objective lens (OL), which has a high telecentricity in a diameter of 11.6 mm and is facilitated with a rotational wheel for switching between various apertures as shown in Fig. 3(a).



Fig. 2. Scatterfield imaging microscopy platform; (a) optical design scheme: S - source, CL - condenser lens, L - relay lens, CBFP - conjugated back focal plane, FS - field stop, BS - beam splitter, TL - tube lens, OL - objective lens, (b) photography of microscopy platform, (c) a catadioptric objective lens and 6-axis sample stage with a navigation microscope located next to the OL.

This CBFP structure enhances the angle-resolved illumination capability to control the partial coherence factor with high reliability. The scattered light engineered for the partial coherence factor and polarization through the CBFP unit and the polarizer (P) is collected by the OL and imaged at the DUV charge coupled device (CCD: Hamamatsu C8000) camera through the tube lens (TL). The CCD pixels with 14 μ m pitch to form scatterfield image correspond to 40 nm at the sample plane. A catadioptric objective lens (Corning Tropel, μ CAT Panther) with NA = 0.13 - 0.74 and a working distance of 8 mm is used for both optical paths as shown in Fig. 2(c). Despite the benefits of the long working distance of the OL, the central mirror obscures the illumination and scattered light less than NA = 0.13. The image field of view (FOV) is 26 μ m in diameter that is magnified to the CCD through TL. Two lenses are used as TL for switching between high-resolution imaging and Fourier plane imaging. Finding specific target within the sample loaded on the stage is difficult due to the immobility of the non-standard OL and the FOV that



Fig. 3. CBFP apertures to control the partial coherence factor and the corresponding illumination NAs: (a) rotating wheel with rectangle apertures with various sizes, (b) relationship of partial coherence factor to aperture width.

is too small to navigate. To resolve this problem, a separate visible microscope with a light emitting diode (LED) of 400 nm wavelength is installed for navigating the target site with a large FOV at the place next to the OL as shown in Fig. 2(c). The center positions of the two FOVs are calibrated using the stage system. The visible microscope module has a right-angle reflector mounted at the end of the navigation objective lens, which deflects the visible light by 90°, allowing the visible focusing beam aligned parallel to the 193 nm focusing beam of the catadioptric objective at a distance.

The partial coherence factor is manipulated using the rectangular apertures mounted in the rotational wheel at the CBFP as shown in Fig. 3(a). The beam shaped by a CBFP aperture are projected onto the back focal plane of the OL through the reduction optics, yielding the Koehler illumination with corresponding NA at the sample plane. The image transferred between the CBFP and the sample plane is optimized for distortion and aberrations through the double telecentric optics. The rectangular apertures with 6 different horizontal widths are used for altering the illumination NA along the direction of the line array. The horizontal widths (x-axis) of the aperture are varied with 2, 4, 6, 8, 10 and 11.6 mm corresponding to the partial coherence factors $\sigma_x = 0.18, 0.34, 0.50, 0.68, 0.85, and 1$, respectively, whereas the vertical widths (y-axis) are fixed with 11.6 mm which corresponds the maximum NA of the OL. The asymmetric illumination shape in x and y directions allows a better responsivity of scattered light to the multiline change in x direction by eliminating unnecessary scattered light in y direction. Figure 3(b) shows the relationship of the aperture width to the partial coherence factor and the maximum angle of the illumination beam at the sample. Figure 4 shows the illumination shapes in the angle space simulated using the geometrical ray tracing with the optical design in Fig. 2(a). The central obscuration at the center is due to a reflection mirror in the catadioptric objective lens as explained above.

The measurements using the optical setup with the partial coherence manipulation unit are performed for a set of nanoscale targets on a MoSi photomask fabricated by e-beam lithography process, as shown in Fig. 5. The target set consists of 10 periodic vertical multilines with the nominal linewidths (half period) ranging 44–80 nm in Fig. 5. Each multiline is fabricated in $100 \times 100 \ \mu\text{m}^2$ as shown in Fig. 5(a). The targets are arrayed in a period of 200 μm and measurements are performed at the left edge indicated by a red line. The actual line dimensions are referenced to the linewidth values evaluated through SEM pictures as shown in Fig. 5(b). The target scatterfield images of 26 μm diameter are taken at the edge area using the CCD during an exposure time of about 940 msec with repeated cycles. This edge measurement which takes both



Fig. 4. Ray tracing diagrams for varied partial coherence factors that are controlled by the rectangular aperture at the CBFP.

the substrate and target intensities at the same time allows the normalization of the intensities scattered at the targets with varied linewidths with respect to the intensity reflected at the substrate that remains constant over the linewidth variation. Locating target sites to the FOV are performed using a 6 axes stage system with an x-y translation of 1 nm resolution.





4. Results and discussions

Figure 6 illustrates the dependence of intensity profile shape on the polarization in the scatterfield imaging microscopy measurements. The illumination beams with two orthogonal linear polarizations incident on a target in the directions perpendicular (x polarization) and parallel (y polarization) to the lines as shown in Fig. 6(a) and 6(d). The resultant scatterfield images with a FOV of about 20 µm in diameter, which is determined by the field stop (FS) aperture size, is shown in Fig. 6(b) and 6(e) for the two polarizations, respectively. Compared to the substrate areas at the left sides of the images, the intensity of the line area at the right side decreases for the x polarization, while it increases for the y polarization. The relative intensity difference at the line area with respect to the polarization can be understood from the absorption effect of the nanoscale gratings with multilayer structures [33]. The intensity variations are shown in Fig. 6(c) and 6(f)as the partial coherence factor is varied using the aperture widths in Fig. 3. The intensity profiles are normalized by the average intensity at the substrate area and each profile is obtained through sampling pixels along the dot lines marked in Fig. 6(b) and 6(e). By evaluating these normalized intensities for linewidth change, measurement sensitivities are analyzed. The dependence of the partial coherence factor is obvious for the x polarization because the illumination beams are same as the modulation direction of the multilines, yielding strong correlation between the partial coherence and the intensity change as well as the edge effect of the partial coherence. On the contrary, the y polarization shows reduced dependence of the partial coherence on the intensity

change, though it has obvious edge effect of the partial coherence. In addition, the reflected light is influenced by the polarization property of the target material which is described by Fresnel equation, although it is affected dominantly by the multiline structure.



Fig. 6. Polarization effect on the intensity profiles scattered at the edge of MoSi multiline targets: (a), (d) - polarization directions relative to the lines, (b), (e) - scatterfield images for two orthogonal polarization, (c), (f) - normalized intensity profiles for partial coherence factors.

Figure 7 lists the full set of the scatterfield intensity variations for the 10 targets ranging 44–80 nm nominal linewidth with the partial coherence factor variations. The actual linewidth values of 44.71–76.49 nm determined by assessing them with SEM and AFM measurements are used for the sensitivity analysis. As expected, the lower the partial coherence factor used for the illumination, which signifies higher imaging coherence, the higher the normalized intensity (NI) observed with more edge ringing artifacts. As the sensitivity is related to the ratio of intensity change to the linewidth (LW) change, high sensitivity regions are in the graphs with $\sigma_x = 0.18$ for x polarization and $\sigma_x = 0.5-1$ for y polarization.

Figure 8 shows the intensity variations at the line areas for the linewidth with respect to the partial coherence factor. It is observed that the intensity profile variation depends on the partial coherence factor highly for x polarization but less for y polarization, since optical scattering correlates to the relative direction of polarization about the modulation direction of the multilines. Some normalized intensity curves with x polarization have higher steepness along the LW direction than with y polarization, while the maximum peak-to-valley of normalized intensities with x polarization ($I_{p-v} = 0.35$) is less than with y polarization ($I_{p-v} = 0.86$).

The sensitivity coefficient maps as the derivatives of the normalized intensities are drawn in Fig. 9 to analyze the partial coherence effect on the measurement sensitivity. The sensitivity coefficient is defined as the partial derivative of the measurements (scatterfield intensity: I) with respect to the measurand (linewidth: L), $c = \partial I/\partial L$ [34,35]. In Fig. 9(a) and 9(b), the curves with x polarization shows higher sensitivity coefficients than with y polarization, while the y polarization has more gradual slopes in sensitivity coefficients than the x polarization. In view of the peak or valley points that signify high sensitivities, both peaks and valleys are present in the x polarization, while only valleys are present in the y polarization. The highest sensitivities are at the partial coherence factor ranging $\sigma_x = 0.18-0.34$, the linewidth range of 50–57 nm, and for x



Fig. 7. Scatterfield intensity distributions at the edges of multiline targets for (a) x polarization and (b) y polarization. Nominal linewidth (half period) ranges 44–80 nm for 6 partial coherence factors, where NI, LW, σ_x are normalized intensity, linewidth, and partial coherence factor in x axis, respectively.



Fig. 8. Normalized scatterfield intensities for the partial coherence factor σ_x with respect to (a) x polarization and (b) y polarization. Curves for 6 partial coherence factors are fitted using averaged data with standard deviations obtained through repeated measurements.

polarization, indicating the optimum illumination zone for achieving high measurement resolving power in the scatterfield imaging microscopy. In this measurement, the best measurement sensitivity is resulted at about 0.2 nm for 54 nm linewidth with a partial coherence factor of 0.18. This sensitivity coefficient map allows for the determination of optimized illumination with the partial coherence factor and polarization for specific targets.



Fig. 9. Sensitivity coefficient map for (a) x polarization and (b) y polarization.

5. Conclusion

It was demonstrated that the partial coherence factor as the degree of coherence in optical imaging system is a significant parameter to enhance the measurement sensitivity for the nanoscale dimensional metrology based on DUV (193 nm) scatterfield imaging microscopy. Normalized intensities scattered at the edges of a wide range of periodic nanoscale multilines on a MoSi photomask was analyzed with respect to varied illumination NA that is controlled by the aperture size and shape at the CBFP. The experimental results show not only that the normalized scatterfield intensity distributions for the nanoscale multilines are nonlinear functions of the partial coherence factor but also that the measurement sensitivity depends strongly on both the partial coherence factor and the target linewidths. Notably the effect of the partial coherence

is highly dependent of the polarization of the illumination beam. From this empirical analysis, the nanoscale dimensional measurement based on scatterfield imaging microscopy requires an optimized partial coherence factor for a certain target size range to obtain high measurement sensitivity. It is expected that the optimization of the partial coherence factor facilitates highly sensitive scatterfield imaging microscopy for dimensional metrology, finding applications in various nanoscale feature metrologies and nanostructure engineering.

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Disclosures

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