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Comparison of far field characterisation of DOEs with a goniometric DUV-scatterometer and a CCD-based system

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We have measured far field diffraction patterns of different diffractive optical elements at an illumination wavelength of 193 nm using a new type of goniometric DUV (deep ultraviolet) scatterometer. This system offers both a high dynamic range and angular resolution. The scatterometer is especially suitable to analyse weak background light like stray light and local variations of the diffraction patterns over the DOEs (diffractive optical element). The measurement results are compared with measurements using a CCD (charge-coupled device)-based imaging DOE measurement system. An excellent agreement of the measured far field distributions is demonstrated. [DOI: 10.2971/jeos.2011.11015s]

Keywords: DOE, optical diffuser, scatterometry, 193 nm, scattering

1 INTRODUCTION

Optical photolithography is the most important manufacturing process in the fabrication of semiconductor components. The tiny structures of these components are fabricated on a silicon wafer. For this purpose structures are first realised on photomasks (reticle) and are then in a wafer stepper transferred from the photomask to a wafer coated with photoresist. This imaging process works in a way similar to an oversized slide projector, but with a demagnification of typically a factor of 4. The quality of the imaging process (above all contrast and resolution) determines crucially the quality and functionality of the produced integrated circuits. One very important part of this imaging process is the type and quality of the illumination of the photomask in the wafer stepper. The illumination optics, which is comparable to the condenser in a slide projector, provides the desired illumination of the photomask. Depending on the type of structures which have to be imaged, the image quality can be significantly improved by applying adapted (e.g. structured) illumination [1, 2]. A high quality and adapted type of illumination can be provided by using high quality DOEs in the illumination light path of the wafer stepper. Since real integrated circuits consist of three dimensional structures these semiconductor components are produced in different subsequent 'slides'. Each slide is produced using a different photomask, which again asks for an adapted illumination corresponding to the type of structures, which have to be imaged.

Different types of DOEs are commonly used in the illumination optics of wafer steppers and -scanners. These are mainly top hat DOEs, which produce from a Gaussian-shaped beam a circular shaped top hat (monopole) beam profile in the illumination plane with a steep slope, and quadrupole DOEs, which produce a beam shape with four poles. In both cases the DOEs are designed to achieve a high intensity level and flat light distribution in the poles while the intensity besides the poles should be minimal. Measurements on both of these types of DOEs will be presented in this paper. To characterise the quality of such kind of DOEs on the one hand and to investigate measurement system induced artefacts we compare the measurement results achieved on a quadrupole DOE with two different set-ups used at Carl Zeiss SMT and at PTB. While the Carl Zeiss SMT set-up uses a CCD-camera based two-dimensional imaging technique with a Fourier lens between sample and detection unit, the PTB uses a goniometric laser scatterometer, which does not require additional optics but which is only able to perform one-dimensional angular scans. Since we assumed that the Fourier lens may cause additional and superposing stray light on the camera, we focus in our comparison of the two set-ups on the residual intensity distribution besides the poles. In the next section we describe the set-ups. Then we present and compare the measurement results and we close with a discussion and conclusions.

2 MEASUREMENT SET-UPS

2.1 Angle resolved DUV scatterometer

Here we present a brief description of the system and its properties. Details about this system are published elsewhere [3].

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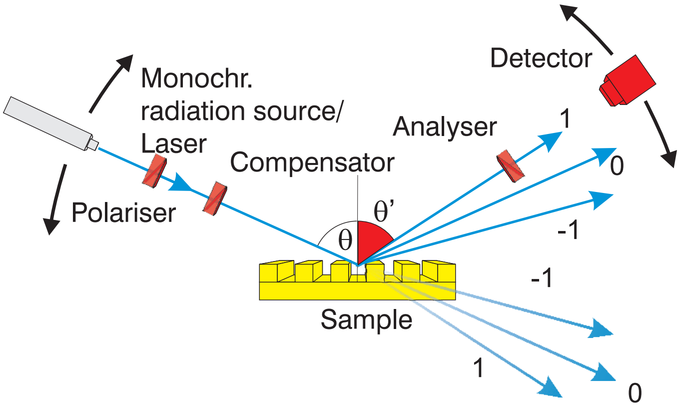

FIG. 1 Scheme of the new DUV hybrid scatterometer. Its main field of application is the characterisation of photomasks.

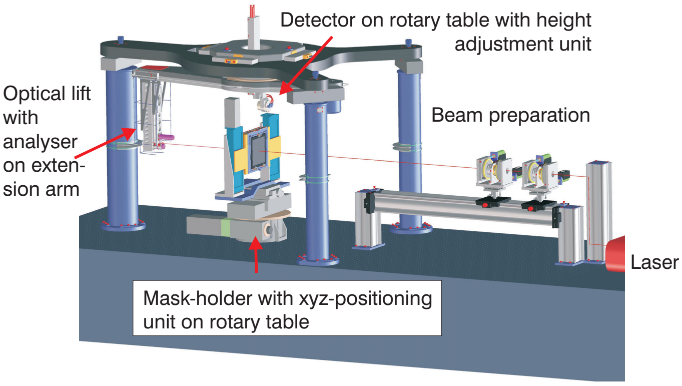

FIG. 2 Technical draft of the DUV scatterometer.

Recently, at PTB a new type of a very flexible goniometric laser scatterometer has been realised [4]. It can be operated in different scatterometric measurement modes. The system provides the possibility to operate at different illumination wavelengths. These variations of measurement conditions allows for an optimisation of measurement sensitivity and to improve the uniqueness of the measurement results. The latter one is of special importance in the scatterometer's main field of application: it is the quantitative dimensional characterisation of structures on photomasks.

Figure 1 shows the measurement scheme for this kind of measurement samples. It also illustrates the basic measurement modes: ellipsometry, diffractometry and measurement of reflection and transmission. The corresponding measurands are polarisation, angle of diffraction and intensity or in more general, the Stokes-vectors from which the Mueller-matrix can be calculated.

Some technical specifications: as radiation source a frequency multiplied Ti:Sa laser provides wavelengths in four ranges (772-840 nm, 386-420 nm, 257-280 nm and 193-210 nm). It is a pulsed system with a repetition rate of 5 kHz. As a beam shaping optics, a telescope with spatial filter is used, which provides a Gaussian beam shape with a variable spot size between about 90 μm and 3 mm on the specimen. The angle of incidence can be varied between ±90° by rotating the photomask holder and the detector can scan almost the entire diffraction plane (±178°). To direct the light diffracted at the specimen to the detector usually an 'optical lift' is used (cf. Figures 2 and 3, respectively for a technical draft and a photograph of the set-up).

FIG. 3 Photo of the DUV hybrid scatterometer. The enclosure can be flushed with nitrogen to avoid absorption by O_2 and O_3.

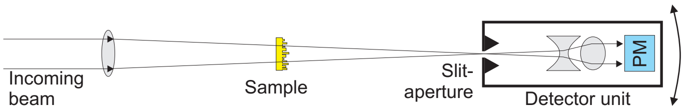

FIG. 4 Principle of measurement for the characterisation of DOEs and diffusers.

2.1.1 Modifications for characterisations of DOEs and optical diffusers

For the characterisation of DOEs some modifications and improvements of the scatterometer were required and applied:

1. A new numerical evaluation methodology for a pulsed light source was applied to increase the detection sensitivity and to decrease the noise level, significantly.

2. To avoid additional stray light by optical elements we did not use the optical lift (cf. Figures 2 and 4). Instead the signal detector unit was placed at the position of the analyser, which is also not necessary for the measurements on the DOEs.

3. Improvement of the detector units (cf. Figure 4): to investigate the stray light background at low levels of light intensity the formerly used signal and reference detectors (trap detectors consisting of three Si photodiodes) have been replaced by solar blind photomultiplier tubes (Hamamatsu type R7154). A slit aperture with a height of 1 mm and a variable width, adjustable according to the beam parameters, has been placed in front of the photomultiplier window to provide high angular resolution. Additionally a beam expanding combination of two lenses was placed between the slit aperture and the detector to ensure a homogeneous illumination of the detection area. Due to the well-known (but still small) non-linearities inherent to photomultipliers this non-linearity was carefully measured and corrected for.

4. Modification of the illumination conditions (cf. Figure 4): to ensure the detection of far field diffraction and to assure that the interaction area is of the order of or greater

than a unit cell of the DOEs the beam was expanded to a diameter of about 3 mm and was slightly focussed on the entrance slit aperture of the signal detector unit. For high angular resolved measurements a slit width of about 100 μm was chosen, which corresponds to the $1/e^2$ beam diameter. With the distance between specimen and slit aperture of 39 cm an angular resolution of up to 0.26 mrad is obtained.

2.1.2 Demonstration measurements

To demonstrate the performance of the scatterometer regarding dynamic range and angular resolution after applying the mentioned improvements, we present measurements on different diffusers specified and suitable for the used wavelength of 193 nm. Measurements have been done in transmission and under normal incidence.

The samples we used for this purpose are two holographic UV diffusers made of fused silica. They are specified to have a transmission of 70% at 190 nm and a homogenous light distribution with design-specific diffusing angles of 15° and 50°, respectively. Additionally we characterised the far field diffraction of a DUV DOE made of fused silica. This DOE has been designed to achieve a top-hat circular shaped far field diffraction with a nominal diffusing angle of 2.9°.

The measured far field scatterograms of both holographic diffusers and the top-hat DOE are shown in Figure 5(a) as a function of the scattering angle. Taking into account that the mean incident laser power is 1 mW the dynamic range of the system can be estimated to be at least seven orders of magnitude corresponding to a mean power down to 100 pW. Additionally Figure 5(b) shows a smaller section of the scatterograms but with the highest angular resolution of 0.26 mrad.

Some notes on the measurement results: for both holographic diffusers the width of the far field diffraction is significantly smaller than specified and both samples show a relatively large and broad background level outside the specified diffusing angles. As expected, this is substantially better for the investigated DOE sample. Here the main energy is concentrated in the pole. Steep slopes are recognisable and distinguish the pole from the background. In the background one can see higher order artefacts. The zeroth order of diffraction can clearly be identified in the scatterogram of the DOE, as a typical artefact for such kinds of samples. But the holographic diffusers also show this effect. Here it is important to know, that the surfaces of the holographic diffusers are not rough but consists of a microlens array with varying focal lengths of the lenses. When manufacturing this kind of refractive diffusers one gets dead zones between the single lenses. Light passing these dead zones appears as a superelevation of the signal in the centre of the scatterogram.

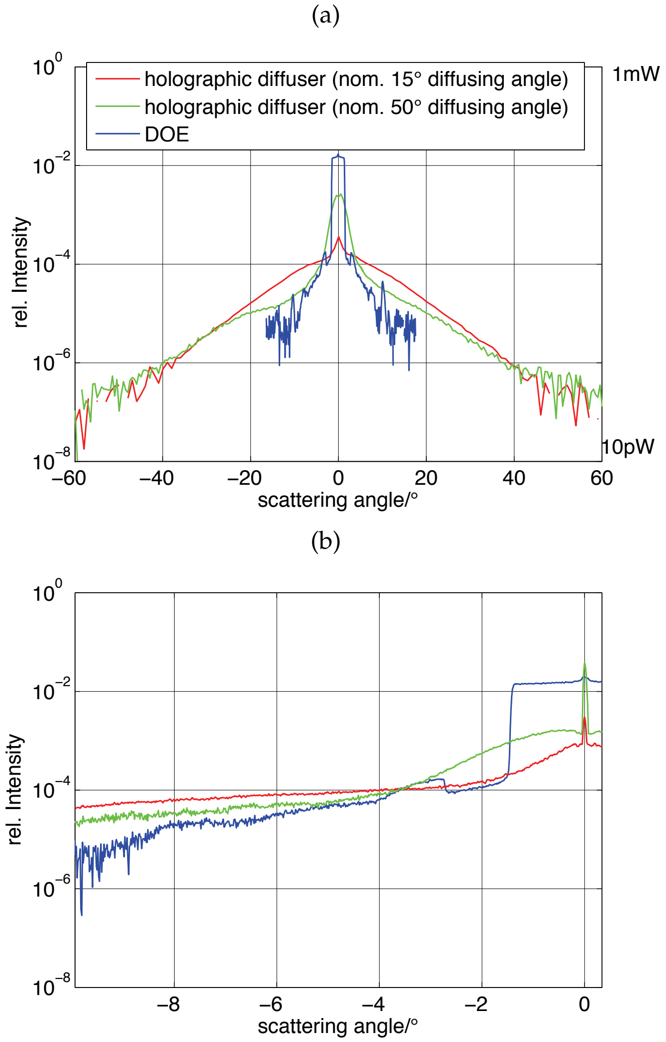

FIG. 5 Measured angular distribution of far field diffraction of two different holographic diffusers with design diffusing angles of 15° and 50°, respectively, characterised with the DUV scatterometer. For comparison a measurement of a DOE based diffuser with a circular far field diffraction pattern is also shown. (a) These measurement examples additionally indicate, that the detection unit of the DUV scatterometer offers now a dynamic range of well above seven orders of magnitude (from incident intensity to noise level) at an illumination wavelength of 193 nm. (b) A scan with a higher angular resolution offers more feature details. For example the zeroth orders of diffraction, which is not only an issue of DOEs but also of the holographic diffusers.

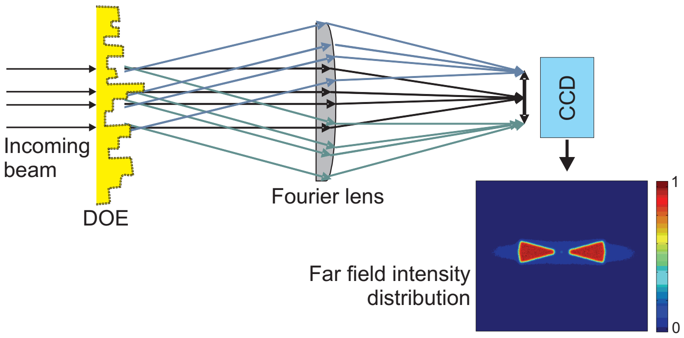

FIG. 6 Optical set-up for the qualification of DOEs at Carl Zeiss SMT.

2.2 CCD based DOE far field measurement set-up

The set-up at Carl Zeiss SMT is shown in Figure 6. It is based on a Fourier transformation of the far field intensity distribution of micro optical components. Collimated and expanded light from a 248 nm or 193 nm excimer laser source is directed under normal incidence onto the object under investigation (spot size: ∼ 10 mm). This corresponds to illumination conditions in a lithography system. The especially designed Fourier lens refracts the scattered light of the whole illuminated spot with negligible distortion onto the CCD-chip. The calibration of the lateral scaling of the generated figure is done with a calibrated grating from the PTB. The scanning over the whole microoptic part and the analysis is done by an automated measurement process followed by an image processing. The whole measurement and analysis takes only a few minutes.

3 MEASUREMENTS AND COMPARISON OF RESULTS

For the comparison of the two different set-ups at Carl Zeiss SMT and PTB different types of DOE in different cross sections were investigated. In Figure 7 the far field intensity distribution of a typical quadrupole DOE as it was measured with the Carl Zeiss SMT set-up is shown. At PTB one-dimensional horizontal cross section scans were performed along the dashed line. Afterwards averaging of 12 (Zeiss) and 8 (PTB) single measurements (repeatability: 0.02% of pole intensity) at different positions on the DOE was performed to eliminate coherence effects (speckles), effects caused by local variations of the DOE, and to take account for different spot sizes of the two systems. These effects led to intensity variations of about 2.5%. The mean distributions are shown in Figure 8. Their agreement is excellent. Only at the slopes of the poles a significant difference can be observed. The real slope of the far field diffraction figure of the DOE is much smaller. Thus the measured slopes are determined by the system inherent angular resolution of the measurement systems: at Carl Zeiss SMT the angular resolution is determined by the divergence of the illumination beam (2.4 mrad). The angular resolution of the PTB system, which is determined by the slit size in front of the photomultiplier, is significantly higher (0.26 mrad). However, the edge slope of the diffraction patterns were not part of this measurement comparison.

The main topic of the measurement comparison was the background stray light of the DOEs outside the poles. This residual stray light shaped up as a good indicator for the quality of the DOE. Even from a theoretical point of view it is not possible to manufacture DOEs without any light around the poles. This would require ideal conditions which generally can not be fulfilled in reality. In practice one gets also additional stray light due to manufacturing imperfections.

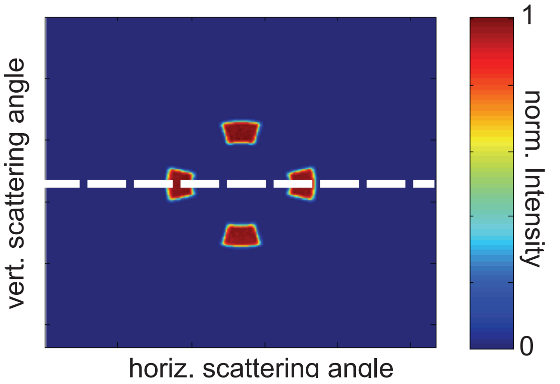

FIG. 7 Far field intensity distribution of a quadrupole DOE, measured at Carl Zeiss SMT. PTB scan has been performed along the dashed line.

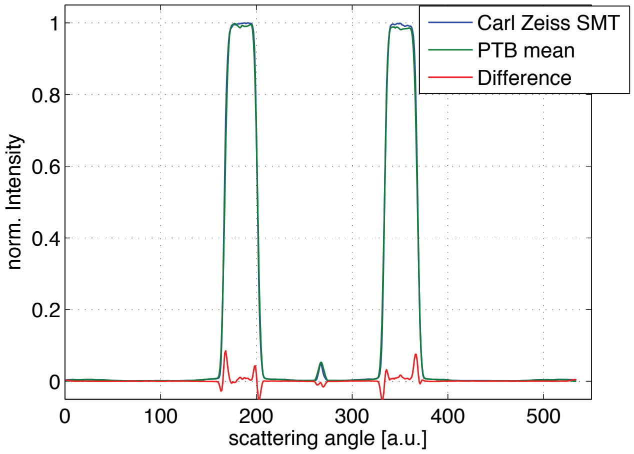

FIG. 8 Comparison of a cross section of a quadrupole far field measured at the PTB and at Carl Zeiss SMT. Due to intellectual property reasons arbitrary units were chosen for scattering angle.

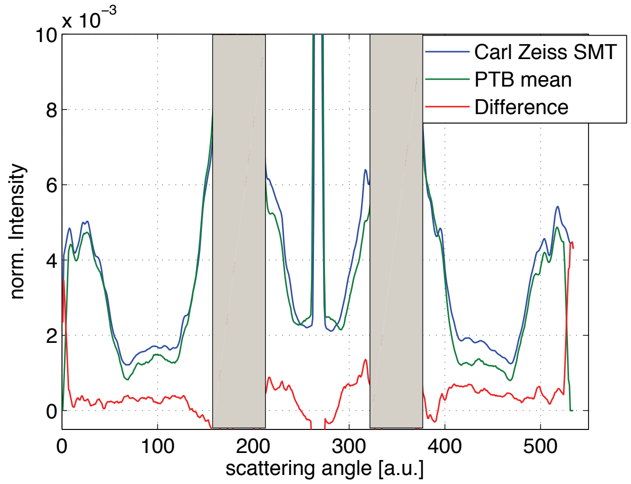

FIG. 9 Diffraction pattern and stray light of a quadrupole DOE. Comparison between PTB and Carl Zeiss SMT.

The sum of both components of the background stray light can be measured with a goniometric scatterometer directly. And in imaging systems additional contributions are expected due to surface and volume scattering at the used imaging optics.

Figure 9 shows a magnified detail of Figure 8: the measured far field distributions of the quadrupole DOE scaled to 1% of the pole intensity. The large deviations between the measurements near the poles exceed the scaling of the graph and are masked out. The mean value of the deviation without the masked region is 0.039%. For all compared measurements the stray light measurements of the PTB give systematically smaller values than the Carl Zeiss SMT measurements and we obtained similar results for the mean values of these deviations for different samples.

4 DISCUSSION AND CONCLUSIONS

The measurement results obtained with the PTB DUV scatterometer and with the CCD-based Carl Zeiss SMT measurement system show in general an excellent agreement both in linearity and shape of the measured diffraction patterns and in many angular resolved details, especially also in the stray light background region. Thus these results demonstrate the suitability of both tools for characterisation of diffusers and DOEs. Only a small residual difference of about 0.039% in the background intensity levels measured in the regions outside the poles could be registered. This can very likely be attributed to a slightly higher stray light level connected with and expected for the Carl Zeiss SMT metrology system due to the implemented imaging optics, the Fourier lens. However, the PTB measurements also show that there is still a significant DOE inherent stray light background level observable. Depending on the type of DOE the PTB and Carl Zeiss SMT measurements show a higher stray light level than calculated for the DOEs using the design data. This additional amount of stray light is expected to be caused by manufacturing uncertainties. We do not assume that other influences to PTB's measurement results like for example the sample and detector adjustment, the quality of the detector's linearity correction and or the performance of the darkfield measurement (achieved with blocked direct beam), exceed the samples intrinsic contribution to the stray light background. Thus both systems are also suitable for the detection of manufacturing uncertainties.

The PTB scatterometer shows some advantages for the characterisation of the far field diffraction of DOEs: the diffraction is directly measured in the angular space without any imaging optics or windows between specimen and detector unit. Therefore, this system shows (nearly) no system inherent stray light. It offers a very high but variable angular resolution and can also offer traceable angle measurements [5]. The high detection dynamic also enables the quantitative characterisation of residual stray light levels introduced by the sample. Additionally the interaction range, i.e. the spot size of the illumination on the sample, is variable between about 90 μm and 3 mm. But it should be taken in mind, that if the spot of the illuminating beam on the sample is smaller than or about the size of the unit cell of the DOE under investigation spatially periodic modifications of the measured diffraction patterns will occur. Thus also a characterisation of the spatial dependence of the diffraction pattern over the DOEs is feasible. Furthermore, in principle also polarisation and depolarisation effects could be measured with this system. And finally we are not limited to a wavelength of 193 nm, but we can perform measurements in the spectral range from DUV to near infrared. The main remaining drawback for DOE characterisation with the PTB scatterometer compared to the Carl Zeiss SMT system is the relatively large measurement time and its limitations to one-dimensional measurements.

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