Characterization of nano-structured surfaces by EUV scatterometry

F Scholze¹, A Kato, C Laubis
Physikalisch-Technische Bundesanstalt, Abbestrasse 2-12, D-10587 Berlin, Germany
E-mail: frank.scholze@ptb.de

Abstract Scatterometry in the UV and the VIS is widely used for the inspection of nano-structured surfaces in, e.g. quantitative wafer metrology in the semiconductor industry. As the structures become progressively smaller, ever fewer propagating diffraction orders exist. Consequently, these few orders do not carry enough information about the structure any more. Particularly the reconstruction of structures without detailed a priori knowledge becomes impossible due to this lack of information. The Physikalisch-Technische Bundesanstalt (PTB) has developed extreme UV (EUV) scatterometry using its EUV reflectometry facility at the electron storage ring BESSY II. The short wavelength of EUV at around 13 nm is advantageous since it provides more propagating diffraction orders compared to the longer wavelength radiation. The short wavelength also increases the sensitivity to small structural features, particularly roughness. We present the application of EUV scatterometry for the characterization of absorber lines with a trapezoidal cross section on semiconductor photo masks and for the characterization of ultra-smooth surfaces of EUV multilayer mirrors. It is shown that structure roughness significantly impacts the scattered diffraction intensities from structured surfaces and must be included in the structure reconstruction algorithms using inverse modelling by FEM. Estimates for the changes in reconstructed geometrical parameters induced by roughness are presented.

1. Introduction

Scatterometry is an indirect measuring method. It relies on the deduction of the properties to be measured, i.e. the geometry of the scattering object, from the influence of this object on the quantities measured, i.e. the diffracted light. There are two principal
approaches. Firstly, the description of diffuse optical scattering from randomly rough surfaces uses disturbance theory and statistical methods to derive expressions for the intensity and directional distribution of the scattered light. The basic relations are outlined in textbooks, e.g. [1]. It should be noted, that the range of spatial frequencies in the surface structure that can be investigated by this method is limited by the wavelength of the radiation, as the existence of real diffraction orders is a precondition for the application of the theory. Secondly, the optical properties of arbitrary structures can be calculated using different methods like FDTD, RCWA, and FEM Maxwell solvers. For reasons of resources and time, however, only rather small domains can be directly computed. Thus this approach is usually applied to periodic structures and a single period of the structure is calculated using periodic boundary conditions to extend it to larger areas. In this sense, scatterometry has become one of the most common techniques in quantitative wafer metrology [2]. Various methods are used, mostly in the spectral range between 200 nm and 1000 nm. As the structures become smaller and smaller, fewer and fewer propagating diffraction orders exist and, consequently, they no longer carry enough information about the structure. For structure pitch measurements by optical goniometry, the smallest pitch that can be determined in backscattering Littrow (incoming and diffracted beam are parallel) geometry is half the wavelength. For wavelengths longer than twice the structure pitch, no diffracted orders exist for any angle of incidence. In this range, the structures work as an effective index medium [3] and detailed a priori knowledge of the geometry is mandatory to derive any structural parameters from the measured effective index. Shorter wavelengths are, therefore, desirable to establish scatterometry as a traceable and absolute metrological method for dimensional measurements of nano-structured surfaces.

At PTB, both approaches are used. Measurements of the diffuse scatter from EUV multilayer mirrors were used to derive the parameters for the interface roughness replication during the layer deposition process [4]. Detailed EUV scatterometric investigations of periodic structures were done at absorber lines of an EUV photomask [5]. It was shown that it is feasible to derive the information on the line profile in periodic areas of lines and spaces by means of rigorous numerical modelling. The comparison with CD measurements using a scanning electron microscope (CD SEM) showed a good correlation of the results [6,7]. Regarding the side wall angle (SWA) of the structures, a remarkable discrepancy of the scatterometry values (below 80°) and the values obtained by AFM measurements (above 85°) was observed. This could recently be explained by the influence of line roughness on the diffraction intensity distribution in angular resolved scatterometry [8]. The latter approach introduced a combination of the above-mentioned complementary interpretations of scatterometry as either a perturbation of specular reflection from a smooth surface or diffraction from a periodically structured surface. Here we comprehensively present recent results for both approaches of scatterometry.

2. Experimental set-up
The data presented here were measured at the EUV reflectometry facility of PTB [9,10] in its laboratory at the storage ring BESSY II. The PTB’s soft X-ray radiometry beamline [11] uses a plane grating monochromator which covers the spectral range from 0.7 nm to
35 nm and was particularly designed to provide highly collimated radiation. Therefore, it uses a long focal length of 8 m in the monochromator and the focusing in the non-dispersive direction is provided by the collecting pre-mirror with a focal length of 17 m. We achieve a collimation of the radiation in the experimental station to better than 200 µrad and the scatter halo of the beam can be suppressed to below 10^{-5} relative intensity at an angle of only 1.7 mrad to the central beam. Using a CCD detector with a 13 µm pixel size at a 1.4 m distance from the sample, we achieve a 10 µrad angular resolution in the detection and can cover about 12 orders of magnitude in intensity from the specular peak to the lowest diffuse scatter intensity, if blocking the specular beam. The measurement scheme for angular resolved scatterometry at periodic structures is presented in Figure 1. Usually, the sample is set at a fixed angle to the incoming radiation and the detector is moved. For the measurement of diffuse scatter from randomly rough surfaces, we use a CCD mounted at a fixed angle with respect to the incoming beam and the sample is rocked, see Figure 2.

### Figure 1. Scheme of scatterometry measurements: The detector angle $\beta$ is scanned at a fixed incidence angle $\alpha$.

### Figure 2. Scheme of small angle diffuse scatter measurement with a CCD detector.

#### 3. Diffuse scatter from super polished mirrors

For short wavelengths below about 30 nm, high reflectance at near normal incidence can only be achieved by multilayer interference reflective coatings. In order to work properly, the interface roughness of these coatings must be extremely low, in the range below 1 nm. For imaging mirrors in EUV optics for semiconductor lithography, roughness amplitudes of well below 0.1 nm (rms) are required over a very broad range of spatial frequencies [12]. These low roughness amplitudes can hardly be directly measured using long wavelength optical radiation scattering. Even more importantly, the resonant reflection from the multilayer coating must be characterized. This requires at-wavelength EUV measurements. In order to access the flare in the optical image of an EUV projection lens, very small scattering angles are most relevant.

As an example, we show data from our reference mirrors used for monitoring the measurement stability of our reflectometer, coated by Fraunhofer IWS in 2001. Figure 3 shows a series of images obtained with the highly collimated beam. The footprint of the
specular reflected beam is extremely narrow and does not have a discernible halo of scatter radiation from the beamline. With a small beamstop blocking only the angular range 2 mrad around the specular direction, the integration time can be increased by a factor of 1000 and the diffuse scatter from the mirror with an almost isotropic distribution is detected. The black shadows in the image arise from the wires used to support the beamstop. A further significant increase in dynamic range by a factor of 20 is obtained by increasing the beamstop diameter to 4 mrad. Note that also the horizontal and vertical scatter lines which arise from beamline apertures are significantly reduced with the larger beamstop. Nevertheless, the scatter from the beamline and from the mirror can be clearly discriminated by the different diameters of the shadow of the beamstop. The origin of the beamline scatter is further from the beamstop than the mirror and thus creates a smaller shadow.

![Figure 3](image)

**Figure 3.** Diffuse scatter of a multilayer coated EUV mirror measured at a 13 nm wavelength with a CCD. The figures are taken with increasing integration time, 0.2 s, 200 s, and 4000 s, from left to right, respectively. For the pictures with longer integration time, the central specular beam was blocked by a beamstop of 2 mm, or respectively 4 mm, in diameter.

Within the almost isotropic distribution of the diffuse scatter, we resolve a mesh-like fine structure. The very low divergence of the radiation provides this high angular resolution. Quasi-periodic structures in the scatter corresponding to spatial roughness frequencies in the range of 100 µm are resolved with about 100 µrad angular resolution (Figure 4, right). The influence of the collimation of the incident radiation is demonstrated by comparison to the image measured with a larger aperture in the beamline (Figure 4, left). There, the high frequency intensity fluctuations are spread out to a speckle-like pattern. The significance of these small angle intensity variations is also illustrated in Figure 5, where the PSD’s derived from the images with 200 s and 4000 s integration time almost completely overlap, indicating that the fluctuations are not signal noise. Images with high angular resolution, as shown in Figure 4, can be used to study geometrical properties of the surface roughness which are not completely random.
4. Angle resolved scatterometry at periodic line structures

The experimental data presented here are obtained from large periodically structured areas at an EUV photomask [5]. It was a negative structure with 540 nm wide and 72 nm thick absorber lines at a pitch of 720 nm, i.e. semi-dense bright lines with 180 nm nominal CD. The measurement method used was angular resolved scatterometry. The scan range of the detector angle \( \beta \) was from -5° to 25°, see Figure 1. The -10th to +14th diffraction order were measured, see Figure 6. As the EUV radiation is resonant with the underlying multilayer reflective coating, the measured diffraction intensities strongly depend on the actual wavelength. We measured at three adjacent wavelengths around the resonance wavelength of 13.65 nm of the multilayer mirror.

The geometrical properties, i.e. the width at the bottom and at the top and the height of the absorber lines were reconstructed by inverse modelling using FEM [6,7]. Three aspects are to be investigated for a proper estimation of the measurement uncertainties. Firstly, the measured diffraction intensities have measurement uncertainties, resulting in uncertainties of about 0.5 nm, or 0.5° SWA for the reconstruction. Secondly, it must be ensured that the model represents the measurement object sufficiently well. A complete description of the sample geometry requires a principally infinite number of parameters, and will, thus, always be an idealization of the real object. Usually it is not possible to simultaneously determine all these parameters from the measured data. Therefore, an a priori judgment is needed as to which parameters are to be kept fixed and which must be adjusted. These considerations contribute uncertainties of typically 1.5 nm, or 1.5° SWA. A detailed
investigation of these first two aspects is given in [13]. Thirdly, there are assumptions in the model which are inherent properties of the mathematical methods used. The assumption that the structures are periodic over a sufficiently large area, i.e. the measurement field, is of the most importance. This assumption is needed to restrict the calculation domain to a size which can be treated numerically within a reasonable time. Therefore, any influence of roughness and other irregularities of the structures cannot be estimated straightforwardly by using the same mathematical algorithms. Using the relations for the impact of line width roughness (LWR) and line edge roughness (LER) on the diffraction intensities recently derived [8], we could show that the roughness induced damping of the diffraction intensities (Figure 7) severely impacts the reconstructed SWA while the mean of the top and the bottom CD is much less affected. The predicted decrease in SWA for a realistic line roughness of $\sigma = 2.5$ nm (rms) is as high as $5^\circ$ and, thus, resolves the observed discrepancy between scatterometry and AFM results.

**Figure 6.** Diffraction intensities for semi-dense nominally 180 nm bright lines at 720 nm pitch. Data for 3 EUV wavelengths at a 6° angle of incidence are shown (green: 13.4 nm, red: 13.65 nm, and blue: 13.92 nm). The lines shown are only to guide the eye.

**Figure 7.** Diffraction pattern (Fraunhofer approximation, red bullets) and the expected intensity pattern with its standard deviation for each diffraction order: LER in the left half, LWR on the right, 165 nm bright lines at 720 nm pitch, $\sigma = 10$ nm, number of lines $N = 100$.

5. Conclusion

At PTB, scatterometry with angular resolution using EUV radiation is used for the characterization of EUV multilayer mirrors. The PSD can be measured up to spatial wavelengths of 10 µm and high angular frequency modulations in the scattered intensity corresponding to a 100 µm feature size can be resolved. On the other hand, scatterometry using discrete diffraction orders from periodic structures is used to determine geometrical structures from inverse modelling. In a detailed investigation of the measurement uncertainties, it is shown that structural imperfections, like edge roughness, have the highest impact on the reconstruction of the geometrical parameters by angular resolved
scatterometry. An improved modelling of roughness is, therefore, of the utmost importance. A first step to combine the statistical approach with structure reconstruction by FEM calculations is presented.

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