High-precision multilayer coatings and reflectometry for EUV lithography optics

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Abstract. The topic of this paper is the fabrication and characterization of EUV reflective coatings based on molybdenum/silicon (Mo/Si) multilayers. For the fabrication of such nanometer structures, the technologies of magnetron sputter deposition (MSD) and ion beam sputter deposition (IBSD) are used in IWS Dresden. The main challenges for extreme ultraviolet (EUV) optics are high reflectance, precise thickness profiles, low internal stress and long-term stability. Reflectances > 70 %, uniformities > 99.9 % and overall internal stresses < 20 MPa have been reached. In addition to sophisticated deposition technologies, precise metrology tools are mandatory for the characterization of the coatings. Together with a number of partners, IWS Dresden has developed a stand-alone EUV reflectometer that makes it possible to measure EUV reflectance R and peak position λ on substrates with diameters of up to 500 mm. Current improvements of the reflectometer resulted in differences compared to calibrated measurements at PTB/BESSY of $\Delta R = -0.2\ldots-0.6$ % and $\Delta\lambda_{50} = +4\ldots+9$ pm.

Keywords: extreme ultraviolet (EUV) lithography, optics, Mo/Si multilayers, MSD, IBSD, reflectometry
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INTRODUCTION

According to the semiconductor roadmap, the density of structures on integrated circuits has to be doubled every 18 month (Moores law). In order to follow this forecast, in a few years it is necessary to change the operation wavelength used for the illumination process from 193 nm to the EUV range with $\lambda = 13.5$ nm [1]. Since no materials with high EUV transmittances are available, mirrors instead of lenses have to be used in the optical system. Such mirrors consist of superpolished substrates and high-reflective Mo/Si multilayer coatings.

Since the first attempts to grow Mo/Si multilayers for EUV reflection coatings [2], within the last 20 years remarkable progress has been made in improving and understanding structure and growth mechanisms of the nanometer structures. One of the main goals has been to improve the reflectance of the coatings close to the theoretical limit of R = 75 %. Because of the fact that approximately ten reflections are necessary in a realistic EUV illumination system any reflectance improvement of every single mirror remarkably improves the overall throughput of the optical system. Independent from the deposition technology used for the production of the Mo/Si multilayers reflectances close to R = 70 % can be reached (evaporation [3,4], MSD [5-8], IBSD [9]). In this paper we will give a short review about the current status of EUV reflection coatings made by MSD and present first results obtained with a new large-area IBSD machine.

In connection with the development of EUV reflection coatings IWS Dresden together with a number of different partners (Carl Zeiss SMT AG Oberkochen, Physikalisch-Technische Bundesanstalt PTB Berlin, BESTEC GmbH Berlin, Max-Born-Institut Berlin, AIS GmbH Dresden) has built an EUV reflectometer suitable for the characterization of optics with diameters of up to 500 mm [10]. The working principle is based on set-ups that have been published in the literature already several years ago [11,12]. In this paper we will summarize the short-term reproducibility of the measured peak positions and reflectances. Additionally we will show the comparison of reflectance spectra of multilayers with different EUV peak positions between 13 and 14 nm measured at PTB/BESSY II and our reflectometer.

EUV REFLECTION COATINGS

As mentioned above several deposition techniques can be used to coat substrates with highly reflective Mo/Si multilayers. In the past we intensively studied pulsed laser deposition (PLD) and MSD. With both technologies tiny barrier layers were applied between the molybdenum and silicon single layers in order to improve the EUV reflectance [6]. Concerning highest possible reflectances MSD has been shown to be the most suitable technology with R = 70.1 % (angle of incidence $\alpha = 1.5$ °, peak wavelength $\lambda = 13.3$ nm) and R = 71.4 % ($\alpha = 22.5$ °, $\lambda = 12.5$ nm). The layer thickness uniformities that can be obtained with MSD are > 99.9 % on substrates with diameters of 150 mm. By applying stress compensation layers the overall stress of the coatings could be reduced down to $|\sigma| < 20$ MPa [13]. Long-term measurements made from PTB at BESSY II show no reflectance altering and no EUV peak shift within a time period of 2 years if barrier layers are used. Without barrier layers the center wavelength decreases by 10-15 pm [14].

While MSD is the favorite option for the deposition of EUV projection optics, IBSD will probably be applied for the deposition of Mo/Si multilayers on mask substrates and on collection optics. The advantages of IBSD compared to MSD are the lower defect levels and the lower sensitivity of the multilayer reflectance to substrate roughness [9]. The new approach of the IBSD machine that we have developed together with the company Roth&Rau Wüstenbrand, Germany, is that linear sources with a length of 400 mm are used (figure 1). This concept ensures the scalability of the process to even larger substrates. Today, we are able to handle substrates with diameters of up to 200 mm via the load-lock. Larger substrates with lengths of up to 500 mm or with diameters of up to 450 mm have to be introduced in the deposition chamber via the front door. First reflectance and uniformity results of IBSD Mo/Si multilayers are shown in figure 2.

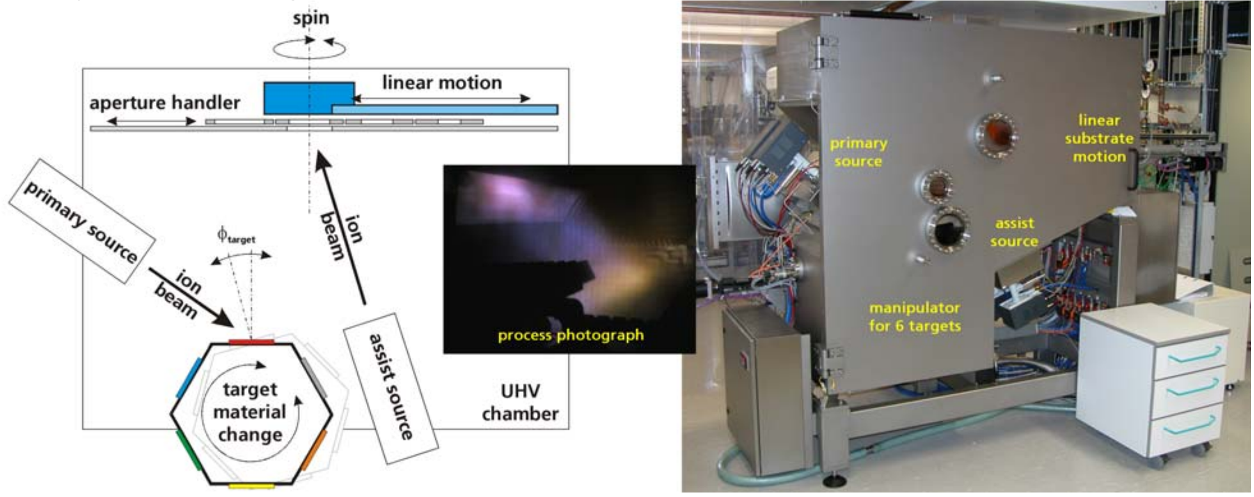


FIGURE 1. Front view of the principle of the large-area IBSD machine developed by the company Roth&Rau Wüstenbrand and IWS Dresden. The chamber is equipped with two linear ECR (electron cyclotron resonance) ion beam sources of 400 mm length. Substrates with diameters of up to 200 mm can be handled via the load-lock at the backside of the deposition chamber. Larger substrates with lengths of up to 500 mm or diameters of up to 450 mm have to be introduced via the front door.

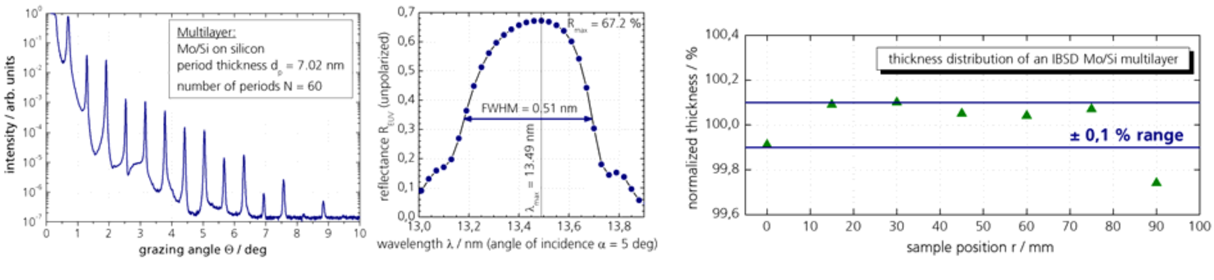


FIGURE 2. Initial results of IBSD Mo/Si multilayers without barrier layers: left hand side: Cu-Kα and EUV reflectographs, right hand side: uniformity obtained on substrates with diameters of 200 mm.

EUV REFLECTOMETRY

Simultaneously to the development of EUV reflective coatings the corresponding characterization methods like reflectometry have to be developed. The availability of EUV light at synchrotron beamlines offers direct access to reflectance measurements [15,16]. However, with the commercialization of EUV components it became necessary to develop laboratory reflectometers that are independent of synchrotrons and directly available next to the coating machine. One successful approach in replacing synchrotron light was to use laser pulse plasma (LPP) sources with gold or tungsten targets [11,12]. This concept was applied to install a laboratory reflectometer that can be used to characterize large-scale optics with diameters of up to 500 mm and masses of up to 30 kg [10].

Short-term reproducibility

Due to the fact that the LPP source of the laboratory reflectometer has not the same stability as a synchrotron source, it requires a lot more effort to perform absolute measurements of reflectance R and peak wavelength λ with the necessary precision. Practically it is much easier to perform EUV reflectance measurements on calibrated samples with known values of R and λ and to consider possible shifts of R and λ for the measurements of unknown samples. The accuracy that can be obtained by this method is then limited by the total uncertainty of the calibrated measurements at PTB/BESSY II and by the short-term reproducibility of the laboratory reflectometer. The carefully analyzed values of the total relative uncertainty values from PTB are 0.14 % for the peak reflectance and 0.014 % for the center wavelength λ_{50} [15].

With the laboratory reflectometer we have to take into account an additional uncertainty arising from the short-term reproducibility of the measurements. In order to quantify these values we regularly perform repeatability experiments where a calibrated sample is measured five times on the same position. A typical result of this procedure is shown in figure 3. The relative standard deviations are $\sigma_{\text{relative, R}} = 0.29$ % and $\sigma_{\text{relative, }\lambda 50} = 0.00085$ %. Therefore the total relative uncertainties of the laboratory reflectometer are increased compared to the PTB values to 0.32 % for the peak reflectance and 0.014 % for the center wavelength λ_{50}. However these values are only valid for flat samples. With curved samples the reflectance of convex and concave surfaces is under- and overestimated, respectively. The quantification of the error contributions depending on the radius of curvature is still under investigations.

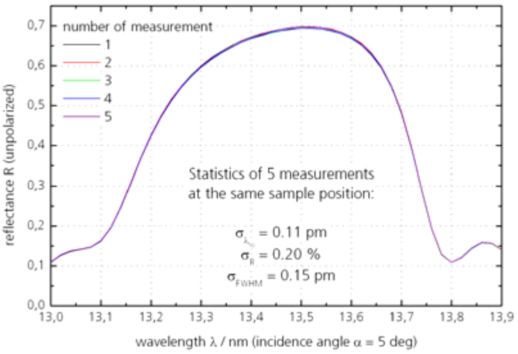
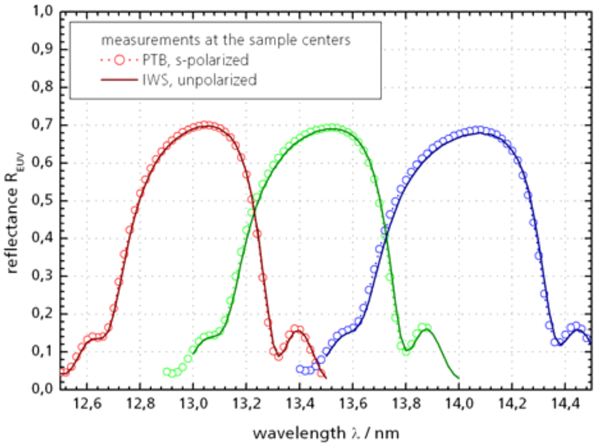


FIGURE 3: Short-term reproducibility of EUV reflectance spectra measured with the laboratory reflectometer. Five identical measurements at the same sample position show standard deviations of the wavelength λ_{50}, reflectance R and half width FWHM of $\sigma_{\lambda 50} = 0.11$ pm, $\sigma_R = 0.20$ % and $\sigma_{FWHM} = 0.15$ pm.

Comparison of measurements from PTB/BESSY II and IWS

In order to get accurate information about the peak reflectance R and center wavelength λ_{50} of unknown samples using the laboratory reflectometer, reflectance spectra of PTB-calibrated samples have to be determined directly before or after the measurements of the unknown samples. Due to the fact that reflectance and wavelength differences between synchrotron and laboratory reflectometry generally also depend on the center wavelength itself we have fabricated multilayers with different period thicknesses. Their reflectance peaks are between 13 and 14 nm (figure 4). By interpolating $\Delta\lambda$ and ΔR we are able to calculate functions $\Delta\lambda = \Delta\lambda(\lambda)$ and $\Delta R = \Delta R(\lambda)$. Of course these functions have to be updated regularly, especially after hardware changes of the source (i.e. target exchange). The observed differences of the half widths of the BRAGG peaks can be explained with the different polarization states of the light. With perpendicular polarized EUV light larger FWHM values are expected than with unpolarized light.



Statistics of 5 measurement points per sample:

Sample 1:
$<\lambda_{50,PTB}> = 12.995$ nm
$<\Delta\lambda> = <\lambda_{50,IWS} - \lambda_{50,PTB}> = (4.48 +/- 0.31)$ pm
$<\Delta R> = <R_{IWS} - R_{PTB}> = (-0.22 +/- 0.09)$ %
$<\Delta FWHM> = <FWHM_{IWS} - FHWM_{PTB}> = (-2.50 +/- 0.24)$ pm

Sample 2:
$<\lambda_{50,PTB}> = 13.453$ nm
$<\Delta\lambda> = <\lambda_{50,IWS} - \lambda_{50,PTB}> = (7.36 +/- 0.34)$ pm
$<\Delta R> = <R_{IWS} - R_{PTB}> = (-0.33 +/- 0.13)$ %
$<\Delta FWHM> = <FWHM_{IWS} - FHWM_{PTB}> = (-1.56 +/- 0.29)$ pm

Sample 3:
$<\lambda_{50,PTB}> = 13.997$ nm
$<\Delta\lambda> = <\lambda_{50,IWS} - \lambda_{50,PTB}> = (8.86 +/- 0.20)$ pm
$<\Delta R> = <R_{IWS} - R_{PTB}> = (-0.58 +/- 0.15)$ %
$<\Delta FWHM> = <FWHM_{IWS} - FHWM_{PTB}> = (-2.30 +/- 0.32)$ pm

FIGURE 4. Comparison of reflectance measurements made at PTB/BESSY II and IWS with the laboratory reflectometer. Three multilayer samples with different EUV peak positions have been measured at 5 positions per sample. The mean values of the differences Δλ, ΔR and ΔFWHM between the measurements have been compared.

In addition to the absolute differences of λ_{50}, R and FWHM between PTB and IWS measurements, the standard deviations of the individual differences should also be noticed. From these values an estimation can be derived how close IWS measurements can predict PTB measurements. In agreement with the reproducibility tests the largest deviation is observed for the differences of the reflectance values. The standard deviation of the absolute differences between PTB and IWS values are between 0.09 and 0.15 % and are predominantly caused by the reproducibility of the IWS measurements. Much smaller deviations occur for the differences of λ_{50} and FWHM. Both are in the order of 0.20-0.35 pm. Hence, the current prediction limits of PTB measurements of λ_{50} and FWHM are given by relative standard deviations of approximately 0.003 % and 0.06 %, respectively.

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