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### Improvements in EUV reflectometry at PTB

F. Scholze, C. Laubis, C. Buchholz, A. Fischer, S. Plöger, F. Scholz, H. Wagner, and G. Ulm

Physikalisch-Technische Bundesanstalt, Abbestraße 2-12, 10587 Berlin, Germany

**Abstract.** The development of EUV lithography is critically based on the availability of suitable metrological equipment. To meet the industry's requirements, the Physikalisch-Technische Bundesanstalt (PTB) operates an EUV reflectometry facility at the electron storage ring BESSY II. It is designed for at-wavelength metrology of full-sized EUVL optics with a maximum weight of 50 kg and a diameter of up to 550 mm. To meet the increasing demands of metrology for future lithography production tools, the measurement uncertainty was permanently reduced. For peak reflectance, an absolute uncertainty of 0.10 % is achieved with a reproducibility of 0.05 %. The uncertainty of 2 pm in the center wavelength is given mainly by the uncertainty for the reference wavelength of the Kr  $3d_{5/2}-5p$  resonance. A long-term reproducibility of 0.8 pm has been demonstrated over a period of about 4 years. We have recently demonstrated repeatability below 0.06 pm. This good repeatability is important for the determination of the coating-thickness gradient in alpha-tool optics.

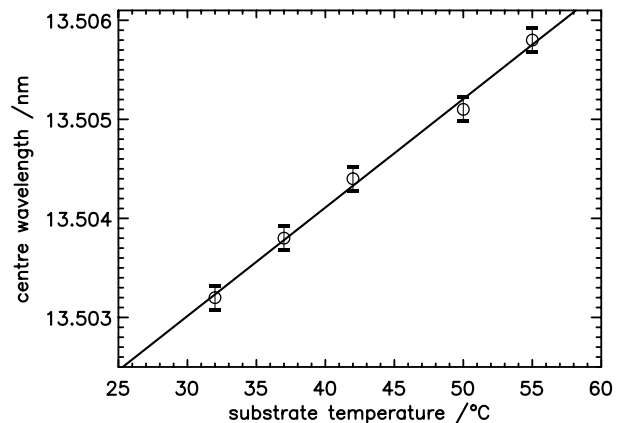
### Introduction

Extreme Ultraviolet Lithography (EUVL) holds the key to the next generation of computer technology. EUVL imaging requires multilayer mirror optics being manufactured with extreme accuracy to ensure uniform illumination of the wafer plane and optimized throughput. As EUVL matures<sup>1</sup>, the requirements for the accuracy of reflectivity and wavelength measurements become tighter. Especially the wavelength for the peak mirror reflectivity should be matched to better than 2.5 pm and the uniformity of reflectance should be better than 0.08 %<sup>2</sup>. In response to this demand, substantial improvements in the total measurement uncertainty and repeatability at the Physikalisch-Technische Bundesanstalt (PTB), Germany's national metrology institute, have been achieved<sup>3</sup>. PTB with its laboratory at the electron storage ring BESSY II, is the European centre of EUV radiometry and supports the national and European industry with high-accuracy at-wavelength measurements in the EUV spectral region, e.g. reflectance measurements as well as life-time and contamination studies<sup>4,5</sup>. The EUV reflectometer allows the measurement of mirrors with a diameter as large as 550 mm, a height of 230 mm, and a weight of up to 50 kg<sup>6</sup>.

### Experimental

The thickness of the Mo/Si multilayer coating of an EUV mirror can be determined from the number of layers which is known from the coating process, and the period which can be determined by reflectometry. This consideration is of practical importance because in the production process, the mirror substrate is polished to the required figure, and afterwards the multilayer coating with a total thickness of about 200 nm is deposited with a required accuracy for the final figure of 0.2 nm<sup>1</sup>. Therefore,

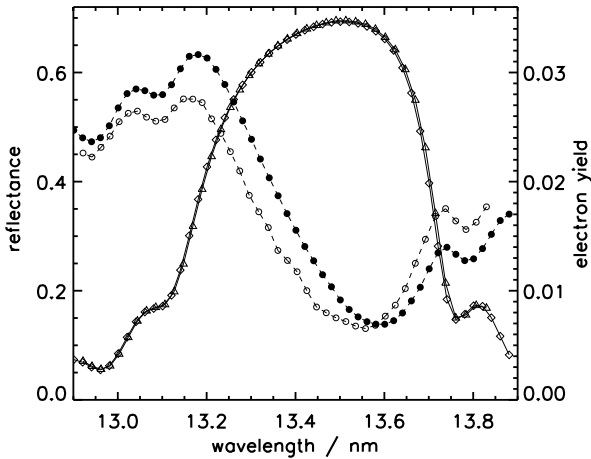
we further investigated the uncertainty contributions in the wavelength measurement. The wavelength uncertainty attributed to the monochromator beamline is published elsewhere<sup>7</sup>. The quantity to be characterized, however, is the double-layer thickness  $d$  of the coating. This is related to the wavelength  $\lambda$  by the Bragg equation  $\lambda = 2 \cdot n \cdot d \cdot \cos(\Theta)$ , with  $n$  the (average) index of refraction, and  $\Theta$  the angle of incidence with respect to the normal. Thus, thermal expansion also contributes to the measurement uncertainty in the EUV reflectometer. The temperature of the samples during measurement is between 25 °C and 30 °C. We measured the spectral reflectance of a Mo/Si multilayer for five temperatures in the range from 27 °C to 55 °C, see Fig. 1. The contribution of pure signal statistics to the uncertainty of the centre wavelength determination is only 0.06 pm ( $1\sigma$ ). A  $2\sigma$ -range is indicated by the error bars. The suspected linear relation holds within this uncertainty. The line shows a linear fit with a thermal expansion coefficient of  $8.1(4)10^{-6} \text{ K}^{-1}$ .



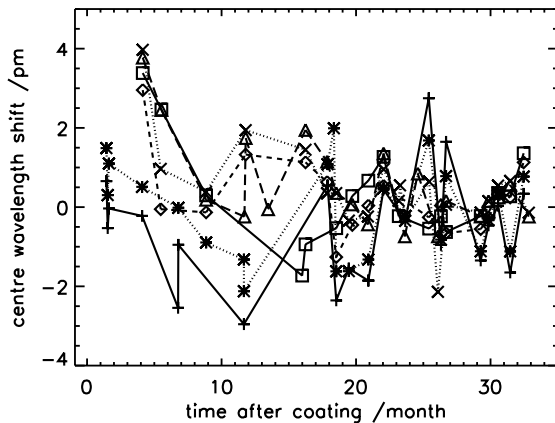
**Figure 1.** Measured shift of the centre wavelength of a mirror with 60(Mo/B4C/Si/C) layers as a function of substrate temperature.

Long-term stability of optical components is one of the key issues for the development of EUV lithography systems. To detect changes that are small enough to extrapolate the measurements to a system-lifetime of several thousands of hours, a high reproducibility of the measurement and a high stability of the (un-illuminated) mirrors themselves is required. Therefore, PTB regularly measures the reflectance of a set of reference mirrors to detect any drifts in the measurements. These mirrors are coated with magnetron sputtering by the Fraunhofer Institute for Material and Beam Technology in Dresden, Germany. The peak reflectance and centre wavelength of these mirrors were measured for a period of 40 months. Fig. 2 shows measurements for one of the mirrors with diffusion barriers in March 2002 and August 2004. The spectral reflectance curves are nearly identical. It was,

however, recently demonstrated that the photoelectron current from the mirror surface<sup>8</sup> can be used to determine the thickness of surface layers, e.g. the build-up of carbon contamination<sup>9</sup>. The photo yield curves obtained are also shown in Fig. 2. The phase-shift of the photocurrent curve indicates an increase in top-layer thickness<sup>3</sup> by about 0.2 nm. Fig. 3 shows the shift in measured peak wavelength for a set of six mirrors and a period of 40 months. Tab. 1 gives a compilation of the present status of the measurement uncertainties at PTB.



**Figure 2.** Reflectance of a mirror measured in March 2002 (triangles) and August 2004 (diamonds), left scale. The circles (open and closed, respectively) are the photocurrent signal, right scale. The reflectance curve is almost identical; the phase-shift of the photocurrent curve indicates an increase in top-layer thickness by about 0.2 nm.



**Figure 3.** Measured shift of the centre wavelength of six EUV mirrors coated with diffusion barrier in December 2001. Data are normalized to the mean. For the four most homogeneous mirrors, the standard deviation of the measurements after month 18 is 0.8 pm.

Peak reflectance	Uncertainty contribution u /%
Stability of normalized intensity	0.02
Inhomogeneity of the detector	0.04
Higher diffraction orders	0.02
Diffuse scattered light	0.08
<b>Total uncertainty of peak reflectance</b>	<b>0.10</b>
Peak wavelength	Uncertainty contribution u /pm
Repeatability of wavelength	0.06
Reproducibility of wavelength (reference to Be K-edge)	1.1
Kr resonance wavelength	1.6
sample temperature ( $\Delta T = 5$ K)	0.6
incidence angle ( $\Delta\Theta = 0.02^\circ$ at $\Theta = 1.5^\circ$ )	0.1
<b>Total uncertainty of peak wavelength</b>	<b>2.0</b>

**Table 1.** Compilation of uncertainty contributions for the measurement of the peak reflectance (upper part) and peak wavelength (lower part) of Mo/Si multilayer mirrors.

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