Radiometry for EUV Lithography

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An essential step in the production of integrated circuits is the structuring of semiconductor wafers for the tracks of the printed circuit boards and transistors. For this purpose, photolithography is applied whose resolution is limited by the optical wavelength. The – currently used – wavelength of an ArF laser of 193 nm is too long to manufacture the small structures which will, in future, be required in a single exposure process. According to the roadmap of the semiconductor manufacturers, extreme ultraviolet (EUV) radiation at a wavelength of 13.5 nm is to be used in future for lithography in chip production with linewidths smaller than 10 nm [1, 2]. The main components of an EUV lithography machine are a powerful EUV plasma radiation source, an illumination system, the reflection mask, and a projection optics which projects a demagnified image of the mask onto the wafer. All these components have specifications which are deemed a technological challenge and which require comprehensive new and further developments. At the same time, the measurement technologies used have to keep pace with developments, especially at the working wavelength around 13 nm (the so-called "at wavelength"). Since there were no suitable EUV radiation sources available for the development of high-accuracy measurement techniques, this "at-wavelength metrology" was, at first, performed worldwide with synchrotron radiation at electron storage rings – in the USA, in particular at the *Center for X-Ray Optics* (CXRO) at the *Advanced Light Source* (ALS) in Berkeley [3] and at NIST in Gaithersburg at the storage ring SURF III [4, 5], and in Europe at PTB in Berlin with its EUV beamlines at the storage rings BESSY I (formerly), BESSY II (currently) and, since October 2013, also at the *Metrology Light Source* (MLS) [6].

EUV Reflectometry

Reflectometry [7] is the main method used at PTB for the "at-wavelength investigation" of components for EUV lithography. In addition to developing powerful EUV radiation sources, the manufacturing of suitable optical components is a great challenge. There are no materials which are transparent for EUV radiation. Therefore, only mirrors can be used as optical components. By using periodic multilayer coatings as Bragg reflectors, a sufficient reflectivity can hereby be attained. The properties of these Mo/Si multilayer coatings must, however, be determined at the working wavelength since – due to the conversion to the working wavelength which would, otherwise, be required – inacceptable uncertainties would arise as a result of the numerical models and material parameters used.

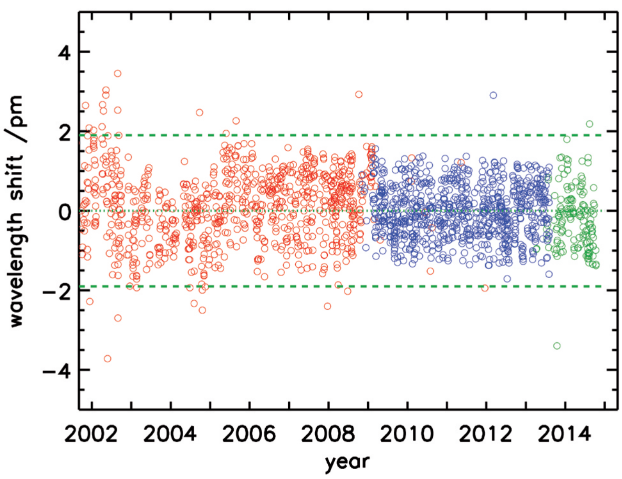

Figure 1:
Results of the daily check of the wavelength by measurement of the Be-K-(red) or the Si-L-(blue) absorption edge at the SX700 beamline. Due to its better stability, Si has been used since 2009 as the reference edge; since September 2013, at the EUVR beamline of the MLS (green).

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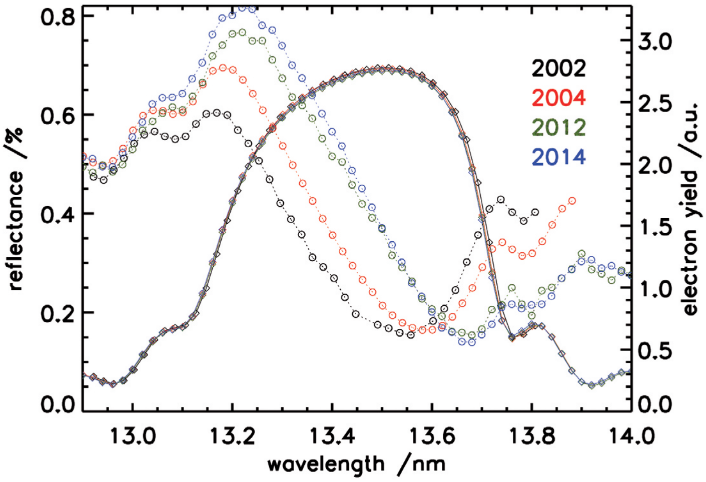

Figure 2:
Repeated measurement of the reflectivity of a mirror with 60 Mo/B_4C/Si/C layers (diamonds, left-hand scale). The photoelectric current of the mirror surface (circles, right-hand scale) was also measured. The phase shift of the signal corresponds to an increase in thickness of the surface layer due to carbon contamination of approx. 1.0 nm.

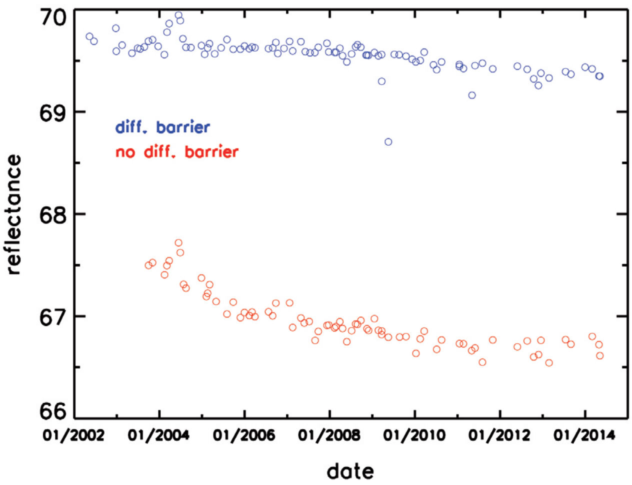

Figure 3:
Reflectivity measured on two EUV mirrors over a period of 12 years (blue: mirror with diffusion barriers; red: mirror without diffusion barrier).

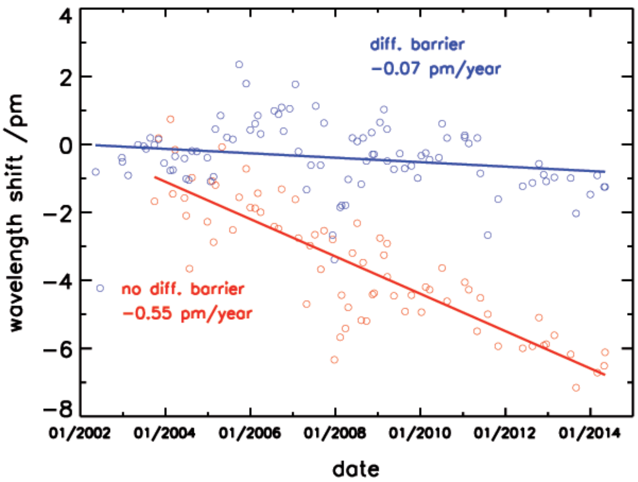

Figure 4:
Measured shift of the central wavelength measured on two EUV mirrors over a period of 12 years (blue: mirror with diffusion barriers; red: mirror without diffusion barrier).

What is particularly important for technological development is the reproducibility of the measurements over long periods of time to be able to safely demonstrate, on the one hand, the asymptotically increasingly smaller progress achieved by the technology and, on the other hand, the long-term stability of the components. The measurement reproducibility of the reflectivity and of the wavelength is therefore continuously checked. Figure 1 shows the wavelength of the absorption edge of a spectral filter [8] which has been measured on a daily basis over a period of more than 10 years for checking purposes in the EUV reflectometer [7] at the SX700 beamline at BESSY II [6, 9] and, from September 2013, at the EUVR beamline at the MLS [6]. The dispersion of the values over longer periods of time results from minimum adjustment losses of the optical beamline components due to, e.g., thermal effects and the settling of the building. For the reproducibility, a tolerance range of 2 pm was defined for the wavelength [10] (green dashed line in Figure 1). When the tolerance is exceeded, the monochromator is re-adjusted.

The reproducibility of the measurements is also checked on a regular basis by means of a group of reference mirrors, whose reflectivity and central wavelength are measured. This allows not only changes in the beamline, but also, for example, possible adjustment deviations or influences due to ageing of the photodetector to be detected in the reflectometer. In order to comply with the Bragg condition for 13.5 nm, the thickness of a double layer of Mo and Si must be approx. 7 nm. These very thin layers are thermodynamically instable and can lead, for example, to molybdenum silicide formation. This causes the mean density to increase, and the thickness of the double layers to decrease, which is considerably accelerated at increased temperatures. For this reason, further intermediate layers are added as diffusion barriers for thermal stabilization. Figure 2 shows measurements of the reflectivity of a mirror with a diffusion-stabilized Mo/Si multilayer system (60 × Mo/B_4C/Si/C) over a period of time of more than 10 years. The changes in the reflectivity and wavelength lie at the detection limit. The photoelectric current of the mirror surface, however, exhibits a clear change. It is correlated with the electric field intensity at the surface of the mirror. Presuming a fixed spatial correlation between the reflected wave train and the multilayer system, this change can only have been caused by a special shift of the surface in relation to the stationary wave field. In this case, this is due to the growth of a carbon contamination layer of approx. 1.0 nm thickness. This shows that the slight change in the reflectivity is clearly due to a slight modification of the sample, and not to measurement errors. This simultaneous measurement of both the reflectivity and the photoelectric current, which was developed at PTB, provides particularly detailed data on minimum changes in the surface state of mirrors which would not be detectable using other methods [11]. In August 2013, the EUV reflectometer [7] moved from the SX700 beamline at BESSY II to the EUVR beamline at the MLS [6]. The good agreement between the measurement from 2014 shown in Figure 2 and the previous ones confirms the good reproducibility, even after the move.

The results obtained with two typical EUV mirrors over a period of time of more than 10 years are shown in Figures 3 and 4. Although the changes measured lie at the detection limit, clear trends become visible. The two mirrors differ from each other by the lack/presence of a diffusion barrier between the Si- and the Mo-layers. In both cases, the reflectivity exhibits a clearly visible downward trend which is, here too, explained by the slow growth of a surface contamination layer. The mirror without a diffusion barrier, however, exhibits – especially at the beginning – a clearly stronger decrease, which suggests a reduction in the optical contrast at the layer interfaces due to the diffusion processes.

The reproducible setting of the wavelength (Figure 1) allows the behavior of EUV mirrors to be checked over long periods of time. Figure 4 shows the shift of the central wavelength for the two above-mentioned EUV mirrors. In the case of the mirror with the diffusion-stabilized multilayer, the central wavelength remains constant over the total period, whereas it – slightly, but clearly – decreases in the case of the mirror without a diffusion barrier. Besides measurement stability over long periods of time, these results simultaneously prove that PTB's measurement uncertainties are sufficient to detect even very small changes over long periods of time. This is an important precondition for lifetime tests as are carried out on the basis of measurements performed by PTB [12].

By commissioning the EUVR beamline at the MLS, PTB has now two beamlines for the EUV spectral range at its disposal [6]. The measuring instruments – the EUV reflectometer at the EUVR beamline of the MLS, and the EUV ellipso-scatterometer at the SX700 beamline at BESSY II [7] – are depicted in Figure 5. Figure 6 shows, as a typical sample for EUV lithography (EUVL), a collector mirror for an EUV laser plasma source with a diameter of 670 mm, mounted in the EUV reflectometer. Figure 7 shows the results of a measurement of the reflectivity of such a mirror across the total optical surface.

An important parameter for the characterization of the collectors for the plasma sources is the polarization state of the incident radiation. The plasma radiation sources emit unpolarized radiation, whereas measurements at PTB are carried out with highly polarized radiation. With the new

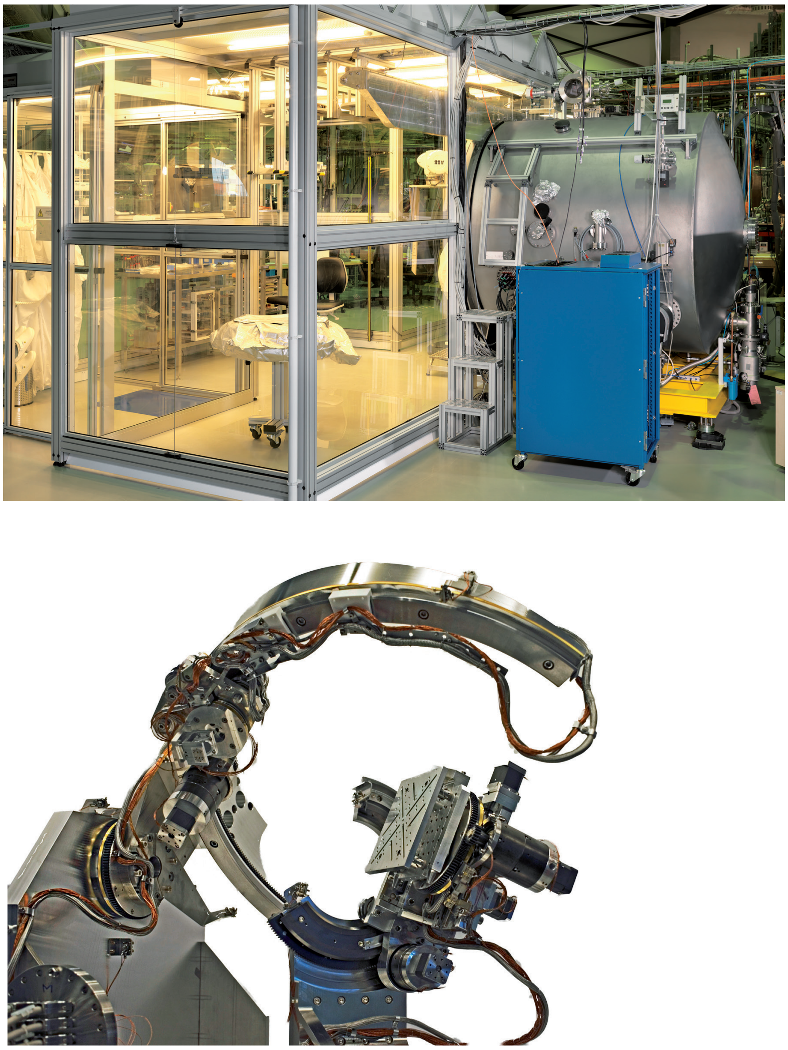

Figure 5:
Measuring instruments for EUV reflectometry: EUV reflectometer with cleanroom environment at the EUVR beamline of the MLS (top), mechanism for sample manipulation and detector displacement of the new EUV ellipso-scatterometer at the SX700 beamline at BESSY II (bottom).

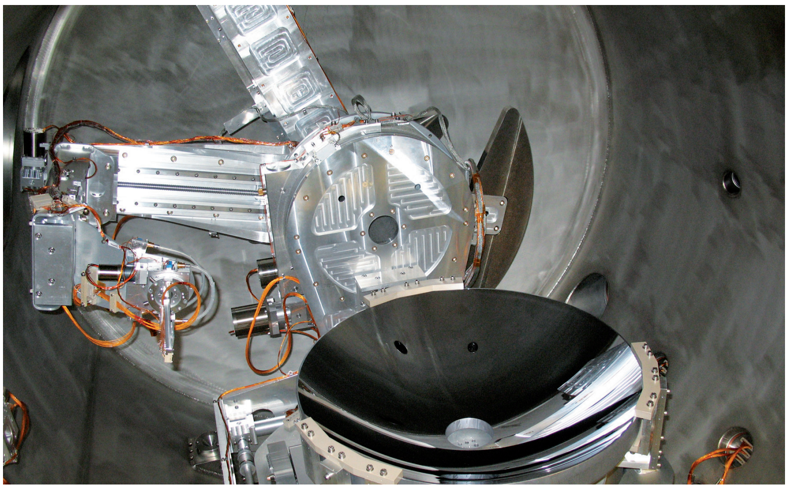

Figure 6:
Collector mirror for an EUV plasma source, mounted on the sample goniometer inside the EUV reflectometer (with the kind permission of Fraunhofer IOF and CYMER).

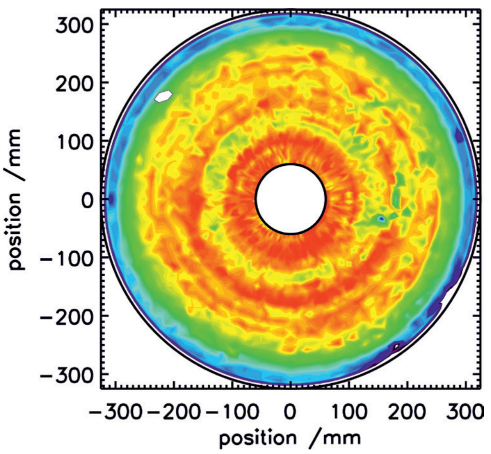

Figure 7:
Example of the measurement result at 13.5 nm for a collector surface with a color scale for the reflectivity from 50 % (dark blue) in steps of 0.1 % up to 55.5 % (red).

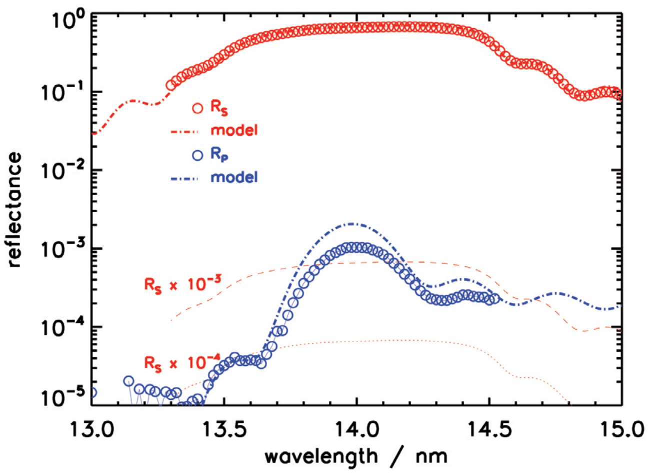

Figure 8:
S and P reflectivity of an EUV mirror around Brewster's angle. For comparison purposes, computed values are shown. The structure parameters were adjusted to the reflectivity measured for S polarization.

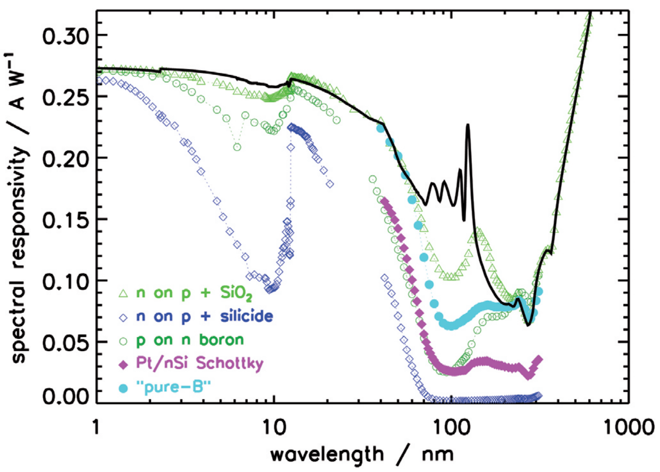

Figure 9:
Spectral responsivity of various photodiodes in the range of soft X-ray radiation as well as in the EUV and the VUV ranges. The black curve shows a model computation for an ideal diode.

ellipso-scatterometer, it is possible to take this into account and to carry out the measurement with high resolution for polarization, similar to the VUV range [7]. Especially the range of the so-called "Brewster's angle", on which the reflection for P polarization is suppressed, is now accessible. The detector used for this purpose is a linear Brewster polarization analyzer [13]. With this set-up, a suppression ratio of 10^4 was measured for the P-oriented component at the Brewster angle of a Mo/Si multilayer mirror (Figure 8). This kind of investigation also makes the optical constants of buried layers accessible.

EUV Detectors

Another important working area to support EUV technologies is the characterization of radiation detectors [14]. When using detectors, it is, in particular, important to know their stability under irradiation and under storage conditions, as well as their sensitivity. PTB has been carrying out numerous investigations in this field for a long time [15]. A major problem is that there are only very few commercially available EUV-stable photodetectors. In a joint project realized together with partners from industry and research, the commercially available detectors were therefore systematically investigated and new variants were developed. PTB participated in these activities through measurements of the spectral responsivity in the VUV and in the EUV ranges as well as through exhaustive investigations of the detector stability [16]. Figure 9 shows typical responsivities of corresponding photodiodes. The new "PureB diodes" [17], developed at TU Delft, are very close to the ideal responsivity and are also stable under irradiation [18].

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