Photonic superlattice multilayers for EUV lithography infrastructure

F. Kuchar and R. Meisels*
Institute of Physics, Montanuniversität Leoben, 8700 Leoben, Austria
*meisels@unileoben.ac.at

The extreme ultraviolet (EUV) is considered as crucial for next-generation lithography, i.e. transistor gate lengths of 7 nm or less [1]. Most EUV lithography systems use a plasma source whose emission peaks at a wavelength λ of 13.5 nm. This wavelength is 14 times shorter than the wavelength of 193 nm used in present-day lithography systems promising greatly improved resolution.

A typical EUV lithography (EUVL) system consists of the EUV source, a collector, illumination optics, a pellicle, a reflective EUV mask, projection optics and finally a resist-coated wafer. A presently widely used EUV source – a CO_2 laser excited tin plasma – has a bandwidth (FWHM) of about 1 nm. The goal for the bandwidth of the illuminating radiation is 2% at 13.5 nm, i.e. approx. 0.3 nm.

In the optical path several mirrors are used, altogether approximately ten. The reason for using mirrors is that at 13.5 nm the refractive index of all chemical elements is governed by atomic-core level transitions and the value of its real part n is close to unity. Therefore, simple refractive elements like lenses cannot be designed. Mirrors, however, can be made on the basis of Bragg's law by employing the constructive interference of multi-layers with the index (n) contrast of two consecutive layers as large as possible but with little absorption (imaginary part of the refractive index). These Bragg reflectors are the established choice for most of the reflecting elements in the system.

The "standard" Bragg reflector with reflectance R of about 0.74 at normal incidence uses 40 to 50 double layers of molybdenum and silicon. At 13.5 nm Mo has a relatively strong deviation (δ= -0.076) of n from 1. Si behaves almost like vacuum (δ= -0.001), yielding the necessary index contrast. The values of the imaginary parts β of n are 0.0064 and 0.0018 for Mo and Si, respectively. This causes weak but not negligible absorption and restricts the number of useful Mo/Si double layers to 40 – 50. The period of this standard Mo/Si Bragg mirror is 6.9 nm. For optimal reflectance the thickness of the Si layer is 60% of the period.

Various concepts of modifying the "standard" Bragg mirror have been reported in the literature, reviewed in [2]. In the present work we investigate the basic properties and possible applications of modified "standard" Bragg reflectors by numerical modelling. In the first step we superimpose a superlattice. It means the superposition of a superstructure on the basic one-dimensional periodic structure by replacing one element in certain layers periodically by another element, e.g. in every fifth double layer of the Mo/Si multilayer Mo is replaced by Si ("SL-5"). This is a well-known concept in semiconductor physics. In the second step we combine two different superlattice structures, e.g. SL-4 and SL-5. The third step is a variation of the period with depth. In these depth-graded multilayers light of different wavelengths is reflected at different depths in the stack. In the fourth step we take variable widths of the EUV source spectrum into account. We weight the reflectance with the spectrum within this width.

The reflectance of the multilayers is calculated by means of the multiple scattering method (MSM) using the MULTEM2 program [3]. It calculates the scattering transfer matrix for each individual element and determines the total scattering matrix as the product of the individual matrices. This matrix is used to output transmittance, reflectance, and absorbance. The MULTEM2 program was modified to take into account the wavelength dependence of the complex dielectric permittivity ε (related to the complex refractive index) [4]. For Mo and Si the permittivity was calculated from the atomic structure factors f_1 and f_2 available from [5].

The main results of our numerical study obtained on the superlattice multilayers, which cannot be produced with the "standard" Mo/Si Bragg mirror, are: 1) Narrowing of the bandwidth of the normal-incidence peak with only slight reduction of the peak reflection (Fig.1). Maintaining a high reflectance is an advantage over other concepts for reducing the bandwidth. Multiple reflections on the mirrors in the optical EUVL system reduce the peak reflectance and narrow the peak width. Examples for five reflections (R^5) are shown for the "standard" and the superlattice-2 mirror. The FWHM is 0.61 and 0.35 nm, resp., after one reflection and 0.42 and 0.21 nm, resp., after five reflections. 2) Filling the reflection gap (Fig.2(a)) between near-normal incidence and total reflection with reflection peaks at certain angles, Fig.2(b). Their number is increased with increasing superlattice number and when combining different superlattices. 3) Depth grading of the periods of the combined superlattices even leads to reflection at all the angles where it is zero in the "standard" mirror, Fig.2(c). However, it is accompanied by a reduced but broader reflectance of the near-normal incidence peak and minima with about one percent reflectance at a few angles. 4) Weighting the reflectance with the spectrum of a EUV source [6], $\langle R \rangle$, smoothens the angle dependence and leads to all-angle reflection, Fig.2(e). In this figure two different widths are considered. Other spectra and different widths can easily be taken into account. Below the onset of total reflection $\langle R \rangle$ values are between 0.07 and 0.28 depending on spectral width and angle, Fig.2(e).

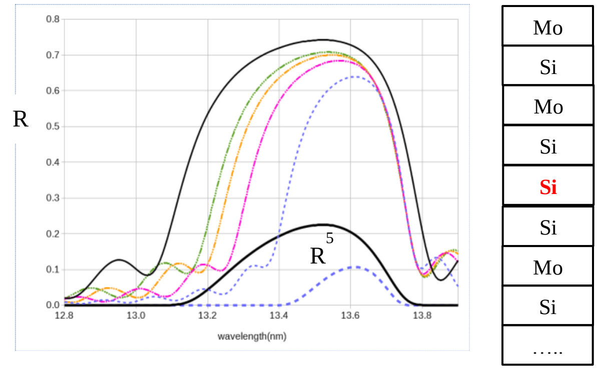
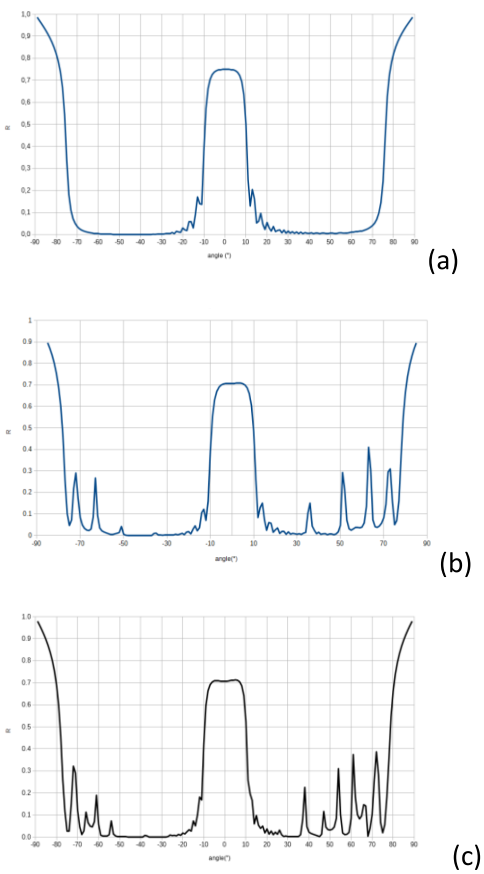


Fig.1. Left: Reflectance *R* at normal incidence of Bragg mirrors with SL-2 (blue), SL-3 (red), SL-4 (yellow), SL-5 (green) and without superlattice (black). The number of double layers is 80, 60, 53, 50 and 40, respectively. This way the number of Mo/Si interfaces is constant (40). Lower black and blue curves are for five reflections. Right: Example for the layer structure (superlattice-3).



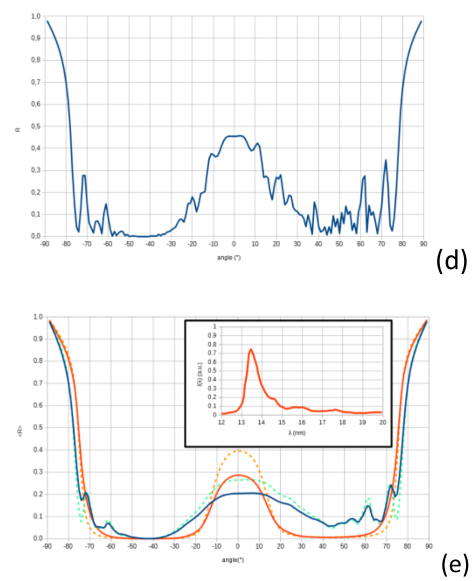


Fig.2 Reflectance as a function of angle of incidence at 13.5 nm: (a) "standard" Bragg mirror, (b) SL-5, (c) SL-5+SL-4, (d) SL5+SL4 with depth grading, (e) Reflectance <*R*> weighted by the Sn emission spectrum of Ref.6 (insert). Full curves: spectral width 12 – 20 nm (blue: graded SL-5+SL-4; red: "standard" mirror). Dashed curves: spectral width 13 - 15 nm (green: graded SL-5+SL-4, red: "standard"). Positive (negative) angle: s (p) polarization.

From result 1) EUV optical systems can benefit where a narrow-band mirror response is needed. This could be in EUV lithography or in monochromators. Results 2) and 3) allow multi-angle, equivalently multi- or broadband-wavelength applications where maximum reflectance is not required, e.g.in EUV spectroscopy or metrology for EUV sources, and higher integral reflectivity in the combination with a broad-band EUV plasma source. Result 4) shows that different parts of the EUV source spectrum can be used at different angles of incidence enhancing the weak all-angle reflection of the graded combined superlattices without weighting.

Regarding the structural design, Bragg mirrors with superlattices are simple modifications of the constant-period "standard" Bragg mirrors. Compared to the latter ones, in the simplest case, only certain layers of one element have to be replaced by layers of the other element without changing the basic double-layer thicknesses and period. With depth grading the modification also means a variation of the period.

References

1. Samuel K. Moore, IEEE Spectrum **55**, 46 (2018).
2. Q. Huang et al., Appl. Phys. Reviews **4**, 011104 (2017).
3. N. Stefanou, et al., Comp. Phys. Comm. **132**, 189 (2000).
4. R. Meisels and F. Kuchar, Optics Express **25**, 32215 (2017).
5. http://henke.lbl.gov/optical_constants/asf.html
6. A. Endo, ch.9, *in* M. Wang, ed., *Lithography*, ISBN 978-953-307-064-3, InTech (2010).