Spectral-purity-enhancing layer for multilayer mirrors

M. M. J. W. van Herpen,[1,*] R. W. E. van de Kruijs,[2] D. J. W. Klunder,[1] E. Louis,[2] A. E. Yakshin,[2]
S. Alonso van der Westen,[2] F. Bijkerk,[2] and V. Banine[3]

[1]*Philips Research Laboratories, Eindhoven, The Netherlands*
[2]*FOM Institute for Plasma Physics Rijnhuizen, P.O. Box 1207, Nieuwegein, The Netherlands*
[3]*ASML, De Run 6501, 5504 DR Veldhoven, The Netherlands*
**Corresponding author: maarten.van.herpen@philips.com*

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We demonstrate, both theoretically and experimentally, that special spectral-purity-enhancing multilayer mirror systems can be designed and fabricated to substantially reduce the level of out-of-band radiation expected in an extreme ultraviolet lithographic tool. A first proof of principle of applying such spectral-purity-enhancement layers showed reduced out-of-band reflectance by a factor of five, while the in-band reflectance is only 4.5% (absolute) less than for a standard capped multilayer. © 2008 Optical Society of America

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An antireflection (AR) coating takes advantage of the wave nature of the light, in particular the phenomenon of destructive interference of light and the dependence of the reflectivity on the index of refraction. By covering a surface with a single coating of 1/4λ thickness, the reflections of radiation with that specific wavelength λ are eliminated, since the ray reflected at the top surface is 180° out of phase with the ray reflected at the lower surface. However, for some applications, one of which will be discussed herein, this 1/4λ thickness is unacceptable and a thinner AR coating is required. We have developed a surprisingly thin AR coating for application to an extreme UV (EUV) multilayer mirror.

EUV lithography, which utilizes radiation around 13.5 nm, is currently the most promising candidate for achieving semiconductor 32 nm half-pitch printable patterns by 2009. Currently available sources for EUV lithography systems are broadband [1,2], and thus in addition to EUV radiation, they generate a significant amount of deep-UV (DUV) radiation. The problem is that the sensitivity of EUV resists may be similar for DUV and EUV wavelengths [3]. Thus, if DUV radiation is allowed to pass through to the wafer, it will expose the resist, inducing contrast loss.

The optical system of an EUV lithography system usually comprises Mo/Si multilayer mirrors that can have up to ~70% reflectance for 13.5 nm radiation, but unfortunately the reflectance in the DUV range is also a considerable fraction of the EUV reflectance, starting at a lowest wavelength of ~100 nm [4]. To suppress the unwanted DUV radiation a so-called spectral purity filter (SPF) may be used. Until now, the only suitable SPFs available were based either on transmission through a thin filter [5,6] or on blazed gratings [7,8].

Transmission filters typically have a transmission that does not exceed 50%, although the best reported result is a Zr–Si filter with an EUV transmission of 75% and a DUV transmission of 0.1% [5]. The efficiency of blazed gratings depends on their output diffraction efficiency, the grating reflectivity, and the slit transmission [7]. Typically, the efficiency of these gratings is below 50%, although practical values up to 63% have been reported [8]. However, even compared with transmission filters, this is still a relatively low EUV efficiency. Furthermore, using diffractive structures requires additional EUV optics, as the grating redirects the incident EUV radiation.

In this Letter, we present a new type of spectral purity filter, which is incorporated into the multilayer optics design as a spectral-purity-enhancing (SPE) layer, thereby eliminating the need for additional optics components and increasing the EUV efficiency of the filter. To suppress a certain out-of-band wavelength range we use an SPE layer that acts as an AR coating. The thickness of the AR coating is chosen such that the out-of-band radiation reflected at the top surface is 180° out of phase with the radiation that propagated one roundtrip through the AR coating. As a result, the reflectivity at these wavelengths is reduced due to destructive interference.

In our case, a thin layer of material, either used as a capping (protection) layer for the multilayer mirror or placed between the multilayer mirror and its (light transmitting) cap layer, is used to enhance the spectral purity of the reflected light. To achieve low EUV losses the thickness of the AR coating should be as thin as possible. By taking advantage of the phase shifts associated with the reflection and transmission on the AR coating we have developed an AR coating with a surprisingly small thickness (below 10 nm) that suppresses DUV light while having low losses for EUV.

As an example, consider a Mo/Si multilayer mirror in vacuum with a thin layer of Si_3N_4 as AR coating (index of refraction for 200 nm light: vacuum $n1=1$, Si_3N_4 $n2=2.62+j*0.174$, amorphous silicon (a-Si) $n3=1.028+j*2.17$ [9]). It is instructive to consider the amplitude reflection and transmission coefficients relevant for the phase difference between the direct reflection and the contribution that has propagated once through the AR coating, as shown in Table 1 (where the values for a Si_3N_4 coating on (a-Si) are shown).

As can be seen, there is a large phase shift of 0.532π due to the reflection at the $Si_3N_4 \rightarrow a$-Si interface. The other phase shifts at the interface are relatively small, and the total phase difference between the direct reflection and the contribution that has propagated once through an Ar coating with infinitely small thickness is 0.52π. To get destructive interference, an additional phase shift of only 0.48π is required. Due to the high real index of the Si_3N_4 layer a thickness of only 9 nm is now sufficient to achieve a total phase difference of π. Thus, by taking advantage of the large phase shift at the interface between the AR coating and the mirror, we were able to significantly reduce the thickness of the AR coating (in this case by a factor of 2).

Not all materials are suited as an SPE layer, but good candidates for SPE layers in the DUV wavelength range are materials such as amorphous carbon, diamond, SiC, and Si_3N_4. In general it can be stated that the real index (for DUV wavelengths) should be as large as possible, because the roundtrip phase shift per unit length for propagation is linear with the real refractive index. Furthermore, the imaginary index should be as small as possible, because the losses in the SPE layer reduce the efficiency of the AR coating. Finally, the EUV absorption should of course also be as low as possible.

We experimentally demonstrated the principle of the SPE layer by coating superpolished silicon substrates with a high-reflectance SPE multilayer coating. The Mo/Si multilayer films were deposited by means of electron-beam deposition and additional ion beam polishing [10–12] in an ultrahigh vacuum system (base pressure during deposition typically 5×10^{-8} mbar). Growth and polishing of the Mo and Si layers were controlled by *in situ* reflectometry using a small built-in soft x-ray source. The roughness is reduced by medium-energy Kr-ion treatment. Finally, a 7 nm Si_3N_4 SPE coating was added to the multilayer stack. More details on the deposition of this layer will be given in a future publication.

These samples were characterized at the Physikalisch Technische Bundesanstalt (PTB) at the Berliner Electronenspeicherring-Gesellschaft für Synchrotronstrahlung storage ring in Berlin [13,14]. The reflectivity of the mirror was measured and compared to the reflectance of standard high-reflectance multilayers terminated with a proprietary capping material. Figure 1 shows the near-normal incidence reflectance for both mirrors in the critical wavelength range of 100–200 nm. It can be seen that the reflectance for the SPE multilayer is substantially lower over the entire out-of-band wavelength range and shows a suppression of a factor of five with respect to the standard coatings.

Table 1. Amplitude Reflection and Transmission at the Interfaces for Si_3N_4 AR Coating (Wavelength of 200 nm)

Interface	Reflection	Transmission
Air $\rightarrow Si_3N_4$	Magnitude: 0.45 Phase: $0.019*\pi$	Magnitude: 0.552 Phase: $-0.015*\pi$
$Si_3N_4 \rightarrow$ (a-Si)	Magnitude: 0.589 Phase: $0.532*\pi$	
$Si_3N_4 \rightarrow$ Air		Magnitude: 1.449 Phase: $0.006*\pi$

The reflectivity curve coincides well with calculated values obtained using IMD software [9,15], although the measured spectral behavior of the reflectance is significantly flatter than the curve calculated using IMD. This is most likely the result of uncertainty in the exact layer thickness and optical constants (density) of the SPE layers or may be the result of a reduced Si_3N_4/vacuum contrast due to surface roughness.

The broadness of the DUV suppression is achieved by a combination of absorption and interference effects. At 130, 160, and 200 nm the transmittance due to absorption is calculated to be 37%, 62%, and 96%, respectively [9]. Combined with data from Fig. 1, this gives a transmittance due to interference of 80%, 30%, and 40%.

The reduction of the EUV reflectance by applying the SPE layer is given in Fig. 2. It shows that there is only a minor drop in EUV reflectance from 66.4% for the standard capped multilayer to 61.9% for the SPE coating, which corresponds with an EUV transmis-

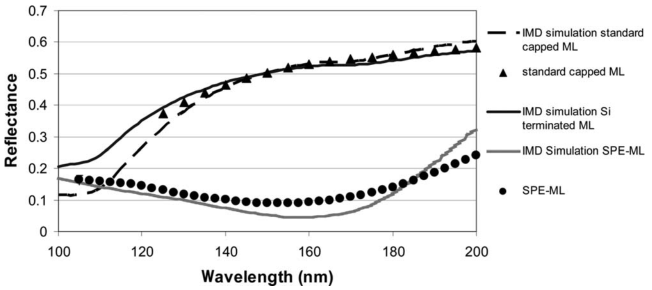

Fig. 1. Near-normal incidence reflectance for a standard capped Mo/Si multilayer (triangles) and a SPE multilayer (dots). The lines represent IMD calculations.

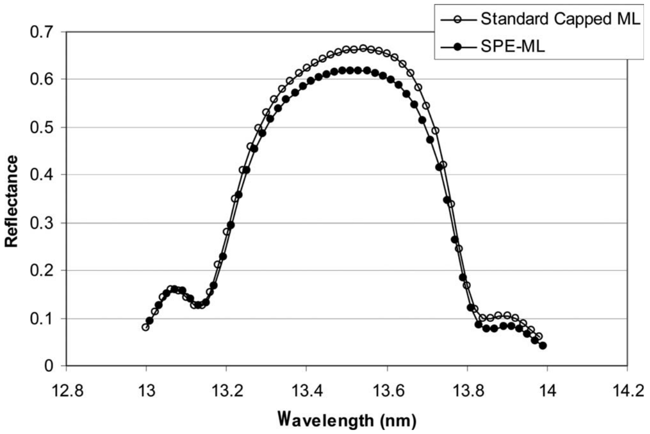

Fig. 2. Near-normal incidence reflectance in the EUV band.

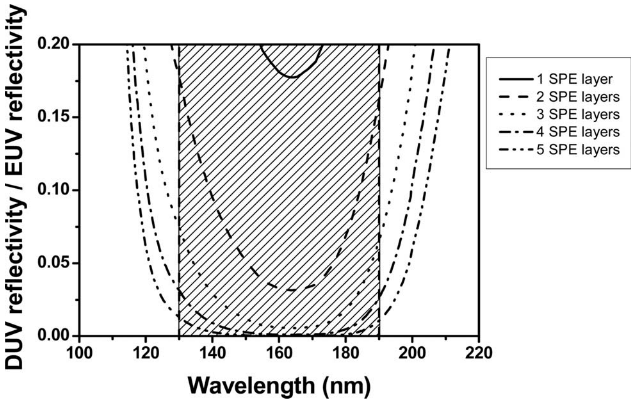

Fig. 3. SPE induced DUV suppression depending on the number of 5 nm Si_3N_4 SPE layers with a standard cap material on top. The shaded area indicates the target wavelength range. The DUV suppression is the ratio of DUV reflectivity and EUV reflectivity. Two SPE layers are sufficient to suppress the DUV power down to below 10%.

sion of the SPE layer of 93% being significantly higher than other SPFs.

Setting the specific requirements for the reduction of out-of-band radiation requires detailed knowledge of the spectral characteristics of the source and the resist sensitivity. The suppression to the required level can be tuned simply by selecting the number of optical elements equipped with an SPE layer, as shown in Figs. 3 and 4. For instance after 4–5 reflections from SPE mirrors, a vacuum-UV suppression of 2 orders of magnitude (for a wavelength range of 130–190 nm) and an EUV transmission of 76%–70% can be obtained, assuming a white emission spectrum of the source.

In conclusion, we have demonstrated, both theoretically and experimentally, that hybrid layered reflective optical elements can be designed that show both near-optimal Bragg-reflective properties in the EUV wavelength range while simultaneously absorbing other selected wavelength bands. Such SPE multilayer mirror systems have been fabricated to substantially reduce the level of undesired DUV radiation expected, for example, in an EUV lithographic machine. A first proof of principle showed reduced out-of-band reflectance by a factor of five, while the in-band reflectance was only 4.5% (absolute) less than for a standard multilayer. Furthermore, since no changes of the configuration of the EUV optics or the optical path are required to apply this multilayer technology-based technique, the degree of out-of-band suppression can simply be adjusted by selecting the number of multilayer-coated elements equipped with these SPE layers.

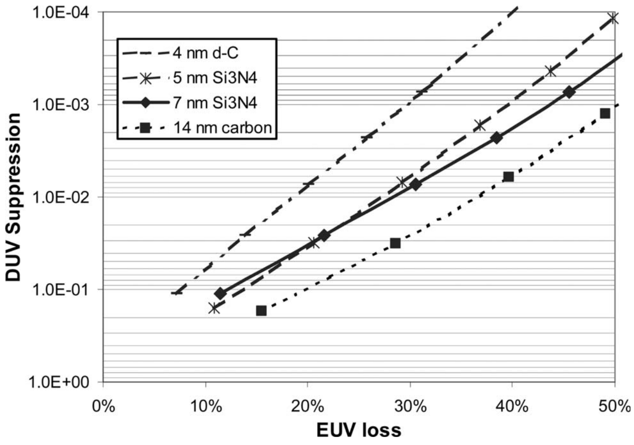

Fig. 4. Average DUV suppression from 130–190 nm for SPE layers of diamond, Si3N_4, and amorphous carbon without further capping layer. A DUV suppression of 10% means that the EUV/DUV ratio improves with one order of magnitude.

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