Optical coatings for soft x-ray applications

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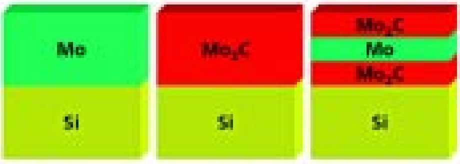

Fig. 1:
Improvement of the thermal stability of Si-based multilayers by the replacement of Mo by Mo_2C and the insertion of Mo_2C diffusion barriers.

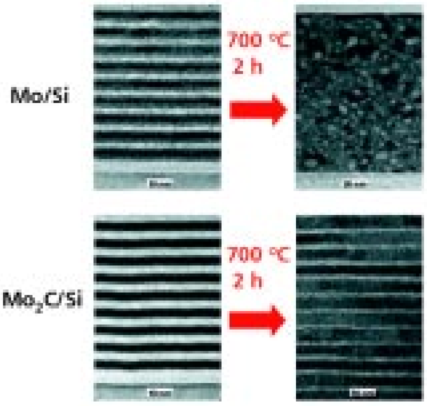

Fig. 2:
TEM images of 7 nm Mo/Si and Mo_2C/Si multilayer mirrors in as-deposited state and after annealing at 700 °C for 2h.

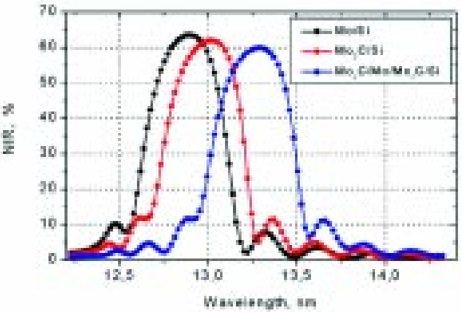

Fig. 3:
Normal incidence reflection (NIR) for different multilayer systems measured with synchrotron radiation at the PTB reflectometer at BESSY.

Introduction

A trend towards the utilization of ever shorter light wavelengths can be observed in many applications, including extreme ultraviolet (EUV) right on up into the range of soft x-rays. Photolithography is one of the most significant applications for short wavelengths in the field of optics. This results from the fact that smaller structures can be replicated on microchips with the help of shorter wavelengths. Thus the semiconductor industry has enormous interest in the continuing development of this technology. By now work is being conducted on lithography techniques for the distant future (NGL – next generation lithography): As compared with other competing technologies, EUV lithography with wavelengths of only 10 to 14 nm appears to have very good prospects. All materials are so absorptive within this spectral range that imaging with lenses is not possible. The optical system must therefore be entirely made up of mirrors. Because the reflectivity at any single interface is extremely small, adequate reflectivity can only be achieved within this spectral range through the use of so-called multilayer mirrors. These consist of many individual layers made of two different materials, each of which has a thickness of about ¼ of the wavelength. Superposition of the reflex amplitudes at all interfaces (interference) results in reflectivity for the entire system which can exceed 70%, for example with the material combination molybdenum and silicon which is commonly used in the EUV range. This presupposes the maintenance of extremely tight accuracy tolerances as regards the thickness of the individual layers, as well as minimal roughness at the interfaces. The fact that the thickness of the layers amounts to only a few atoms represents a great challenge for coating technology, as well as for layer analysis methods.

Multilayer mirrors for EUV

We focused our interest on the development of multilayer mirrors that provide not only high reflectivity, but also a good thermal stability to take into account the heating of the multilayer by EUV irradiation of a plasma source that will be used in future EUV-lithography tools. In fact, we have shown that the thermal stability of Si-based multilayer mirrors can be considerably improved in two ways: (1) The replacement of Mo by Mo_2C and (2) the insertion of thin Mo_2C layers at the silicon interfaces which act as interdiffusion barriers (Fig.1). All multilayer mirrors were prepared by dc-magnetron sputtering, designed for normal incidence at about 13 nm and compared in terms or reflective properties and heat resistance in the temperature range from 200 °C to 700 °C. X-ray scattering, transmission electron microscopy (Fig.2), atomic force microscopy and synchrotron radiation were used for the characterization of the multilayer structures. So far, we achieved a maximum NIR (normal incidence reflectivity) of 65.4 % at 12.9 nm wavelength for Mo/Si, 61.9 % at 13 nm wavelength for Mo_2C/Si and 59.9 % at 13.3 nm wavelength for Mo/Mo_2C/Si/ Mo_2C multilayers in as-deposited state (Fig. 3). The small angle X-ray reflectivity (Fig. 4) and the multilayer period of Mo/Si multilayer mirror drastically decrease after annealing to temperatures above 300 °C, whereas the corresponding changes in Mo_2C/Si and Mo/Mo_2C/Si/ Mo_2C multilayers occur after heating to temperatures above 600 °C and 500 °C, respectively. The high thermal stability and excellent reflective properties of Mo_2C/Si multilayer mirrors provide a good potential for their use as elements in EUV optics under heavy radiation load of plasma, synchrotron etc.

Multilayers mirrors for soft X-rays

The use of thin-film technologies for extremely short wavelengths is not restricted to the field of photolithography. Optics for extremely short wavelengths are also required for x-ray astronomy, for research with the help of synchrotron radiation and for the development of X-ray microscopes. For example, the wavelength range from 2.3 to 4.4 nm, the so-called water window, is of special interest in the field of X-ray microscopy. This energy range is situated between the absorption edges of oxygen and carbon, which means that water is significantly more transmissive for X-ray radiation than are organic molecules. This narrow range of wavelengths thus allows for good contrast for the examination of biological objects.
The development of multilayer mirrors for this wavelength range is even more difficult than in the EUV range because individual layers of less than 1 nm thickness must be produced, and the number of periods must be increased to approximately 300. We have chosen the material combination Cr/Sc because of its high reflective properties and the good interface stability. The multilayers deposited by magnetron sputtering show smooth interfaces in the multilayer stack even for very small period spacings, as shown in TEM-images (Fig. 5).
The reflectivity of the samples was measured at the PTB reflectometer at BESSY in Berlin using the water window wavelength l = 3.16 nm. For normal incidence the measured reflectivity is 6%. For d = 1.86 nm we obtain R = 13% and for d = 3.17 nm the measured reflectivity is R = 30% (Fig. 6).

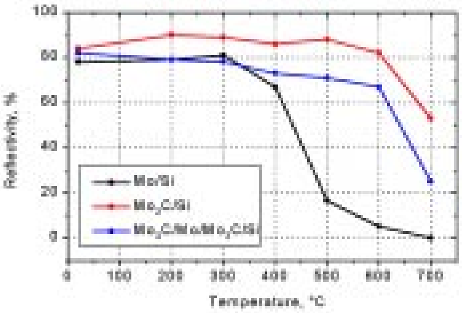

Fig. 4:
Evolution of reflectivity at l = 0.154 nm for different multilayer systems with increase of annealing temperature.

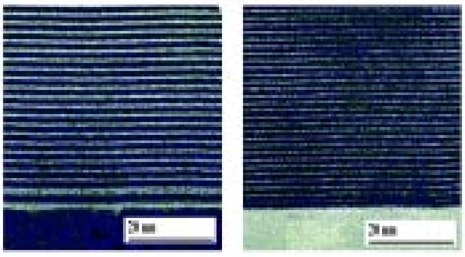

Fig. 5:
TEM images of Cr/Sc multilayers with periods 2.35 nm and 1.57 nm.

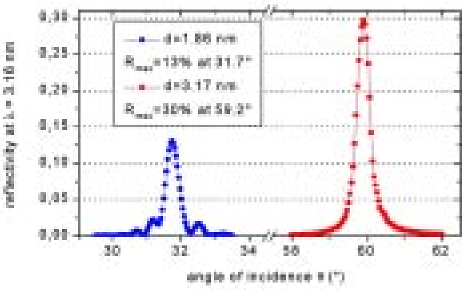

Fig. 6:
Reflectivity of Cr/Sc multilayers at the water window wavelength l = 3.16 nm.