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ENHANCEMENT OF DIFFRACTION GRATING EFFICIENCIES IN THE SOFT X-RAY REGION BY A MULTILAYER COATING.

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ABSTRACT

In this paper is shown that an optimized multilayer coating on the premirror and on the grating of a grazing incidence monochromator would improve the transmission up to an order of magnitude for a special scan mode. The measured reflectivities for this 3 period multilayer coating are compared to those for a thin gold film. For both objects the reflectivities can successfully be calculated using recently published optical constants and taking into account the surface roughness. Evaporated onto a blazed grating an identical multilayer improves the efficiency at the anticipated working points just as expected from intuitive arguments.

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INTRODUCTION

In the VUV- and soft x-ray region with photon energies between 100 eV and 1000 eV (wavelength region: 12.4 nm $\geq \lambda \geq$ 1.24 nm) the reflectivity of common mirror coating materials is very small for steep angles of incidence /1/. The same holds true for the diffraction efficiencies of reflection gratings. For near normal incidence it is shown that the reflectivity of mirrors can be improved by multilayer coatings /2/, this is f.e. applied in a scanning microscope for soft x-rays using a Schwarzschild objective at about λ = 10 nm /3/. Keski-Kuha /4/ has shown that also the grating efficiency at normal incidence and λ = 30.4 nm can be improved if one coats a grating with a multilayer. Multilayer coatings can give also reflectivity enhancement at grazing incidence /2/. Discussed here is the application in monochromators for the soft x-ray region that can use variable angles of incidence onto a premirror and a grating. In our new monochromator BUMBLE BEE the standard wavelength scan is made by simultaneously rotating a premirror and a grating axis /5/. This is the scanning mode also used in double crystal monochromators, where the crystal planes of the two crystals must remain parallel to each other. But crystal monochromators cannot cover the above mentioned photon energy range due to the unavailability of naturally occurring crystals with appropriate lattice constants /6/. Here multilayer coated mirrors i.e. artificial crystals with very large lattice constants would be the solution. But these objects have some decisive disadvantages. For reasonable resolution a great number of periods is necessary /7/. But these periods are difficult to produce with the required reproducibility in the period length. Additionally these mirrors will not satisfactorily suppress the whole spectrum of wavelengths that can be reflected at normal incidence ($\lambda \geq$ 30 nm), so these contributions must be suppressed by other techniques that will always affect the photon flux at the nominal wavelength. These problems can be solved, if one uses a grating for one of the elements, then the contribution of longer wavelength radiation in the monochromatized beam is no longer a problem. The resolution will then also be given by the grating parameters and not by the number of periods in the multilayer coating. This is the idea that will be discussed and compared to experimental data in more detail in the following.

In the BUMBLE BEE design /5/ the monochromatized radiation after the exit slit is parallel displaced to the incident beam just as in a double crystal monochromator. The grating with 1200 lines/mm has a blaze angle of 1.0° and the original proposed wavelength scan mode is working in blaze maximum, i.e. the beam is always reflected on the groove facets. The blaze angle and this mode were chosen to give good suppression of higher orders in the monochromatized spectrum /5/, and indeed the higher order contributions are far below 1% in the whole energy range that can be covered with this mode /8/. In this orientation the angles of incidence onto the premirror and onto the grating facets are identical, in analogy to a double crystal monochromator the facet planes can be identified with the crystal lattice planes. If the transmission of the instrument is very low in certain wavelength regions an optimized multilayer with identical period lengths on both objects (premirror and grating) should be able to enhance simultaneously the reflectivity and the efficiency and therefor the transmission of this configuration.

EXPERIMENTAL

To see what improvement can be achieved first the reflectivity of the premirror for the blaze maximum working curve is inspected. A glass mirror with very low surface roughness was prepared similar to the mirror installed in the monochromator. The

reflectivities of this mirror and the data for the other objects to be described were measured with the UHV-Reflectometer described by Hogrefe et al /9/. This instrument that is permanently installed at HASYLAB receives the monochromatized radiation in the soft x-ray region 50 eV to 1000 eV (24 nm $\geq \lambda \geq$ 1.25 nm) from the monochromator BUMBLE BEE that is connected to the storage ring DORIS. The principle and characteristic data of this instrument are described in great detail elsewhere /5,8/, the measuring technique will be discussed in reference /10/. All data reported here were measured with the approximately linear polarized electric field vector perpendicular to the plane of incidence, this orientation is usually referred to as s-polarisation. The signal caused by higher order light is always below 1%. In all the systematic errors in the data are below 2%, so that the error bars in most cases are comparable with the symbol sizes. To allow a clear presentation of the data these bars are not drawn.

DISCUSSION

In fig. 1 are shown as dots the reflectivities measured for the gold mirror (film thickness 28 nm) versus the angle of grazing incidence ϕ for 5 different wavelengths. The results are typical for mirrors that have been evaporated in the reflectometer in high vacuum (10^{-6} torr - ion getter pumps) with very low deposition rate (1 nm/min) and 500 mm distance between the evaporation source and the sample. These data are usually better than the reflectivities of mirrors that were evaporated in the same pressure range in standard evaporation chambers that are evacuated with diffusion pumps. In principal optical constants can be derived in a multiangle fit procedure /11/ from the angle dependent curves in fig. 1. But this was not done because it exists a useful set of optical constants. The solid line in fig. 1 shows the reflectivities calculated for the thin gold film on a carbon substrate. For these calculations optical constants that can be derived from atomic scattering factors given by Henke et al /12/ were used. Due to the lack of data for glass the optical constants of carbon were used for the substrate (in a comparative investigation the differences in the reflectivities of thin gold films on glass or carbon layers were found to be very small). The formulas given by Heavens /13/ for the s-reflectivity of a thin film were taken and the straylight losses caused by the surface roughness were included by multiplication of the final result according to /14/

(1) $$R = R_0 \exp[-\{(4\pi/\lambda)\, \sigma \sin\phi\}^2].$$

Here λ is the wavelength, σ the RMS surface roughness and ϕ the angle of grazing incidence. For all used wavelengths the surface roughness of $\sigma = 1$ nm gives the best agreement between the measured and the calculated data. In all this agreement is very good and thus shows the applicability of the atomic scattering factors /12/ over a large photon energy interval. Indicated in fig. 1 with arrows are the angles where the premirror is used in the BUMBLE BEE monochromator in blaze maximum mode. For wavelengths $\lambda \geq 2.5$ nm it is obvious that the mirror reflectivities at these points are always small, so that with a multilayer coating the transmission should be improvable.

In scaling the data reported by Haelbich and Kunz /2/ for a gold/carbon multilayer we optimized the reflectivity at the just mentioned working points with a 3 period multilayer on a gold film (18 nm). Below the carbon k-absorption edge the absorption coefficients of these materials differ significantly from each other so that according to Spiller /15/ good reflectivity enhancement caused by multiple reflections should be achievable. The reflectivities measured for this multilayer mirror are shown in fig. 2. Actually for wavelengths above the carbon K-edge the observed local maxima nearly coincide with the working points indicated by arrows. Now the calculations for the

reflectivity were made using the thin film formulas /13/ in a recursion technique. The surface roughness was again included by multiplying finally the result according to equation (1). A fit was made to the experimental data by a try and error procedure, the varied parameters were the individual thicknesses of the layers and the surface roughness. The best agreement is reached for 3 identical periods with thicknesses of 6.5 nm Au and 11.7 nm C and a surface roughness of $\sigma = 1.2$ nm. This last term is increased compared to the simple mirror because of the larger total film thickness of approximately 72.6 nm. By varying the thicknesses of the layers in a computer simulation it was not possible to improve the reflectivity at the anticipated working points furthermore. Compared to the gold mirror this multilayer mirror gives two to four times the reflectivity at the working points for wavelengths above the carbon K-edge. For wavelengths below this edge the reflectivity is nearly unaffected. So a mirror with this coating should be successfully usable in the BUMBLE BEE monochromator in the spectral range 4.4 nm $\leq \lambda \leq$ 20 nm.

Since we had no duplicate of the grating installed in the monochromator, we evaporated the optimized multilayer on a blazed grating with also 1200 lines/mm but with blaze angle of 1.5° instead of the optimal 1.0°. The efficiency of this grating that is found to be of high quality is discussed elsewhere /10/. The multilayer covers an area 30 mm in length and approximately 8 mm in width. Because of the beam size the investigation for this object has to be limited for angles of grazing incidence above 2.5°, so that the anticipated working points can be inspected for wavelength as short as $\lambda = 1.8$ nm. Diffraction orders are here in the classical mounting counted positive if they lie between the incident and the specularly reflected beam. The data measured for the +1. order in the orientation with nonvignetting grooves are shown in fig. 3 for two different wavelengths. Not shown are calculated data, as discussed in reference /10/ the slopes of the curves for the grating coated with the single gold layer can very well be calculated with the differential method /16/ of the exact electromagnetic theory. The multilayer can to the knowledge of the author until now not be calculated, because the program /17/ existing for this situation has numerical problems if the total film thickness is greater than the wavelength. So we can here only compare the measured data for the single coating and the multilayer coating. For wavelengths below the carbon K-edge the efficiency enhancement is very small as it is also the case for the flat mirror, hence these data are not presented here. For $\lambda = 5$ nm and $\lambda = 10$ nm we find as expected local efficiency maxima in fig. 3 just at the arrows indicating the working points. For these points the efficiency is significantly improved compared to the single coating and the enhancement factors agree with those already found for the multilayer coating on a flat mirror compared to the single layer. The efficiency for the 2. order of $\lambda = 5$ nm at the working points for $\lambda = 10$ nm is nearly unchanged at about 0.01%, hence this multilayer coating on the grating will further reduce the second order contribution at certain wavelengths.

Consequently a combination of premirror and grating with this optimized multilayer would improve the instrument transmission in blaze maximum mode up to an order of magnitude with good suppression of higher orders.

Until now components with this optimized multilayer are not installed in the monochromator BUMBLE BEE, however a multilayer with slightly larger period length can be used (the thus reduced transmission enhancement through this multilayer is obvious in fig. 4 of reference /8/ if one compares the output for the multilayer coating with that for the gold mirror).

Another application may also be of interest. Nevière et al /18,19,20/ tried to optimize the grating profile for monochromators that use only one grating in a constant deviation configuration. For all instruments that deflect the beam by 20° the transmission of the monochromator drops to 1% or less at the low wavelength limit with $\lambda = 5$ nm. The working point for blaze maximum and $\lambda = 5$ nm in fig. 3 represents just this beam deflection of 20°. With the multilayer coating an efficiency of 4% was achieved that is better than all the data calculated /18,19,20/ for gratings with a single coating. So it is possible to improve the instrument transmission at the low wavelength limit with the described multilayer. However in other intervals this object will give lower efficiencies than a normal grating. So this optimized coating can f.e. be a solution if in an existing instrument the geometry shall not be changed and a number of gratings can be exchanged in situ.

CONCLUSION

We have presented the reflectivities measured for a simple gold mirror and for a multilayer coating. These data are in very good agreement with the calculations that use the optical constants tabulated by Henke et al. For wavelength above the k-edge of carbon it is found that the multilayer gives better reflectivity than a single coating over a large wavelength interval for a special monochromator working mode. From intuitive arguments an identical multilayer coating should also enhance the efficiency of a blazed grating. And indeed the efficiency could be improved in the same amount as the mirror reflectivity at the anticipated working angles. So the combination of these two objects can improve the instrument transmission by about an order of magnitude while it has less influence on the data for the second order contribution.

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FIGURE CAPTIONS

Fig. 1

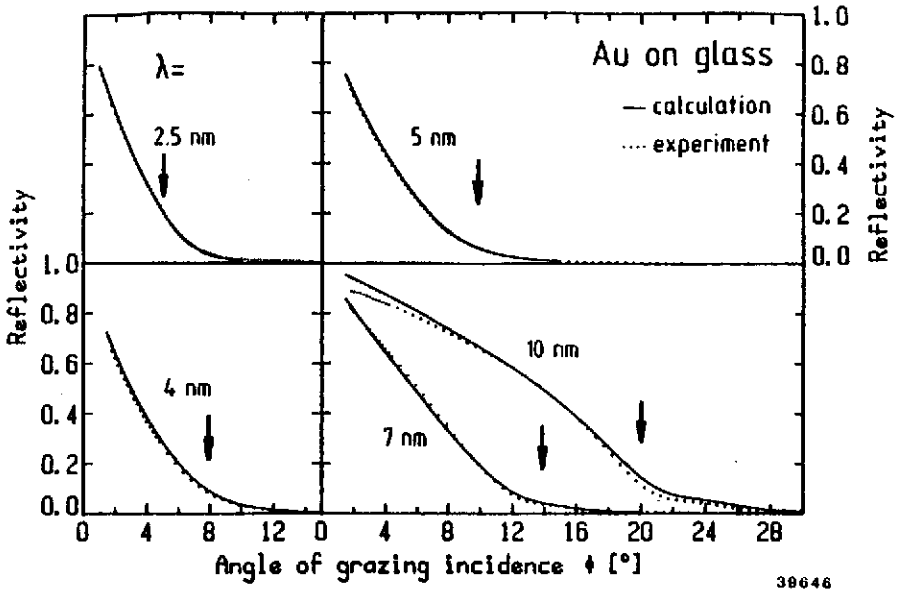
Reflectivity of a thin gold film (28 nm) on glass dependent on the angle of grazing incidence for 5 different wavelengths: comparison of the measured data with a calculation for a gold film on carbon. With arrows are marked the working points of the premirror in the BUMBLE BEE monochromator (see text).

Fig. 2

Reflectivity of a mirror coated with a multilayer versus the angle of grazing incidence for 5 different wavelengths: comparison of the experimental results with the calculation for 3 periods of 6.5 nm Au and 11.7 nm C on gold. Arrows indicate the working points of the premirror in the BUMBLE BEE monochromator (see text).

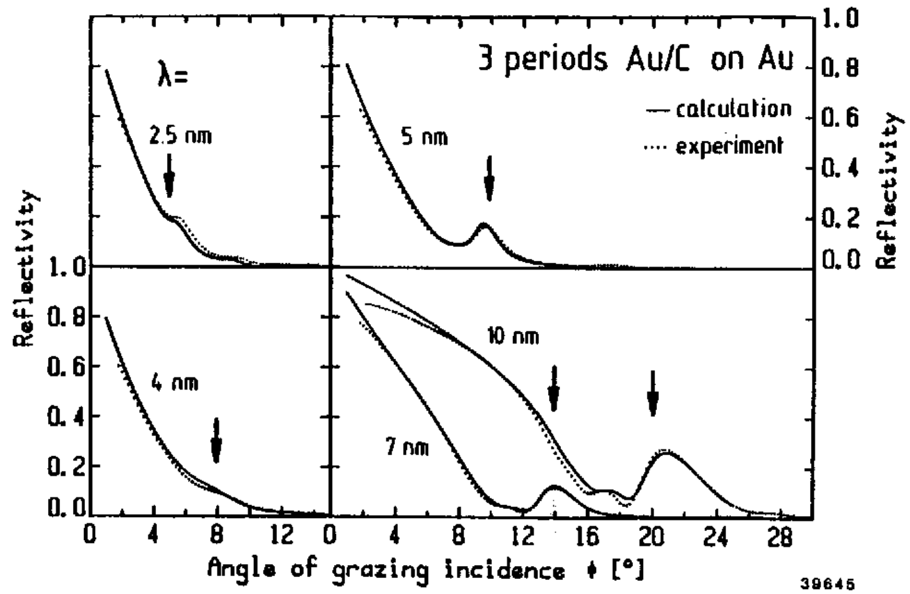
Fig. 3

Grating efficiencies measured for the +1. order of diffraction versus the angle of grazing incidence for 2 different wavelengths: comparison of the data for a gold coated and a multilayer coated blazed grating (1200 lines/mm and blaze angle 1.5°). The arrows mark the anticipated working points (see text).



Au on glass
— calculation
···· experiment
λ=
2.5 nm
5 nm
4 nm
7 nm
10 nm
Reflectivity
1.0
0.8
0.6
0.4
0.2
0.0
Angle of grazing incidence ϕ [°]
0
4
8
12
16
20
24
28
39646

Fig. 1



3 periods Au/C on Au
— calculation
···· experiment
λ=
2.5 nm
5 nm
4 nm
7 nm
10 nm
Reflectivity
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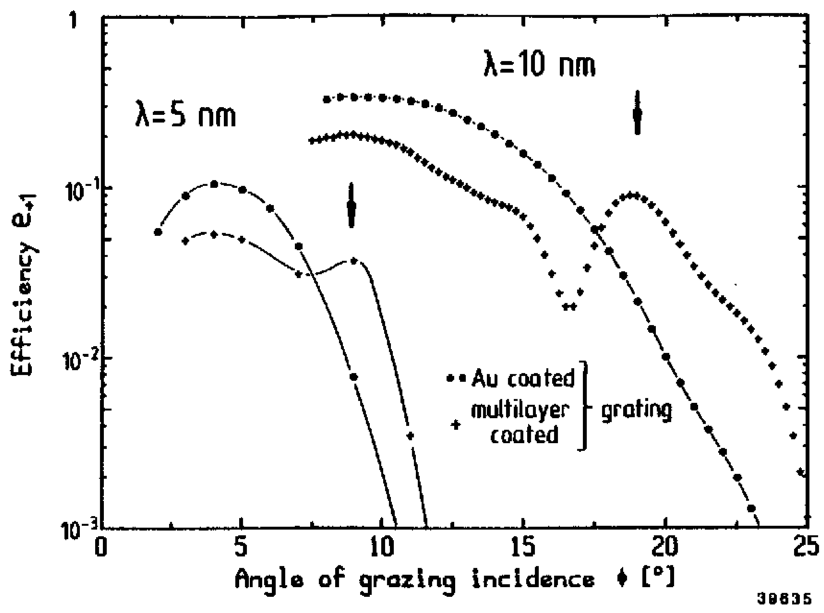
0.6
0.4
0.2
0.0
Angle of grazing incidence ϕ [°]
0
4
8
12
16
20
24
28
39645

Fig. 2



λ=10 nm
λ=5 nm
Au coated
multilayer coated
grating
Efficiency e_{+1}
Angle of grazing incidence ϕ [°]
1
10^{-1}
10^{-2}
10^{-3}
0
5
10
15
20
25
39635

Fig. 3

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