THIN SILICON CARBIDE COATING OF THE PRIMARY MIRROR OF VUV IMAGING INSTRUMENTS OF SOLAR ORBITER

Udo Schühle[(1)], Hein Uhlig[(2)], Werner Curdt[(1)], Thorsten Feigl[(2)], Armin Theissen[(1)], Luca Teriaca[(1)]

[(1)] *Max-Planck-Institut für Sonnensystemforschung, Max-Planck-Str. 2, 37191 Katlenburg-Lindau (Germany)*
Email: schuehle@mps.mpg.de, curdt@mps.mpg.de, theissen@mps.mpg.de, teriaca@mps.mpg.de

[(2)] *Fraunhofer-Institut für Angewandte Optik und Feinmechanik, Albert-Einstein-Str. 7, 07745 Jena (Germany)*
Email: thorsten.feigl@iof.fraunhofer.de, hein.uhlig@iof.fraunhofer.de

ABSTRACT

We investigate the thermo-optical and vacuum-ultraviolet properties of thin silicon carbide (SiC) coatings on transparent substrates in view of their use for Solar Orbiter remote sensing VUV instrumentation. We have made experimental studies with thin SiC coatings on quartz plates to evaluate their reflective properties in the VUV spectral range between 58 nm and 123 nm. We discuss the results in relation to the visible and near infrared optical properties of the samples. A thin SiC coating of 10 nm thickness is shown to be a very promising compromise between high VUV reflectivity and low vis/IR absorption. The overall absorption of the solar spectrum by such a mirror is less than 8 %. This will be beneficial for instruments requiring a large aperture due to diffraction and radiometric limitation, in coping with the thermal heat load during the Solar Orbiter mission. As an example, we propose a design of the primary telescope mirror for the Extreme Ultraviolet Spectrometer (EUS).

1. INTRODUCTION

Mirrors of silicon carbide (SiC) have been shown to be the material of choice for telescopes and spectrometers in space for their high reflectance at normal incidence in the wide spectral range between 50 nm and 160 nm. High-resolution spectroscopy and imaging at vacuum-ultraviolet wavelengths requires apertures of several centimeters diameter to achieve the desired, often diffraction limited, image quality and the signal levels required for a high-cadence imaging. The thermal environment of Solar Orbiter, however, sets very tight limits on the instrument's aperture sizes due to the high solar irradiation (up to 20 solar constants) during the perihelion passage. In addition, the variable heat input during the orbit has to be managed by the spacecraft. In fact, the heat load entering through the aperture of the instruments has to be managed and conducted to a space radiator. During non-operational phases of the instruments, especially when instrument aperture doors are closed, the missing heat input must be provided by compensation heaters. Since the area for space radiators and the electrical power for compensation heaters of the spacecraft are limited, the design goal is to minimise the amount of thermal heat that is to be absorbed inside the instrument.

To reduce the heat load on the primary mirror of a telescope, a dichroic design that does not absorb the solar visible and near infrared but preferentially reflects the VUV radiation can greatly relax such technical difficulties.

For this reason, we have produced samples of mirrors to measure the thermo-optical and VUV specular properties as a function of thickness of the SiC coating. We have made experimental studies with thin SiC coatings on quartz plates to evaluate their reflective properties in the VUV spectral range between 58 nm and 123.6 nm and discuss the results in relation to their visible and near infrared optical properties.
The results have been used to make a model calculation of the heat load under solar irradiation in space. The promising results lead us to propose a design for the primary telescope mirror of a VUV spectrometer for Solar Orbiter.

2. TEST SETUP AND MEASUREMENTS

Three samples of quartz with a diameter of 25 mm and 1 mm thickness were chosen for the coating with silicon carbide.
Coating thicknesses of 4.6, 8.9, and 17.6 nm have been applied to the samples at the Fraunhofer Institut für Angewandte Optik und Feinmechanik (IFO). Their transmission and reflectance curves between 200 nm and 1000 nm have been measured. From these photo-metric measurements the resulting absorption has been calculated over the entire spectral range, thus providing the thermo-optical data needed for a model calculation of the solar heat flow.
The reflectivity in the EUV/VUV has been measured with quartz samples of 10 mm thickness which have

been coated simultaneously with the 1-mm substrates to the same coating thickness. The SiC coatings have been applied by sputter deposition The reflectivity has been compared to a reference sample of SiC-CVD coating on a bulk SiC mirror at the wavelengths 58.4 nm, 73.5 nm, 104.4 nm, and 123.6 nm using the SUMER reflectometer chamber at Max Planck Institute for Solar System Research (MPS).

As a radiation source the reflectometer employs an open capillary discharge device, operated with the rare gases helium, neon, argon, and krypton. The emission of the EUV source was better than 95% monochromatic, after passing through a vacuum-monochromator. The signal was detected with a photodiode (AXUV diode from IRD inc., USA) mounted on a rotatable arm, concentric with the rotation axis of the sample holder. The dark and background (stray light) signal of the diode was 10 nA for these measurements and it was subtracted from the measured signal. The reflectivity was measured at a high vacuum pressure of $5x10^{-7}$ hPa.

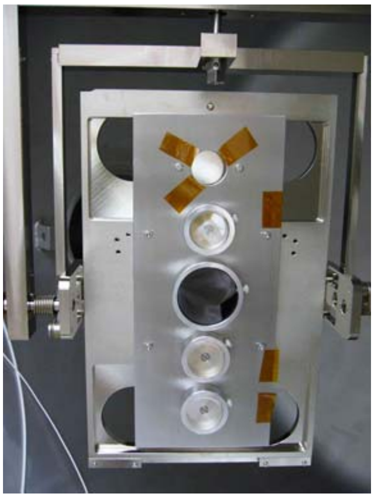

Figure 1: The sample holder inside the reflectometer with one blank quartz plate, three quartz samples coated with thin SiC (transparent) and the solid SiC/CVD reference sample (black) in the centre of the sample holder. A manipulator allows sample movements with five degrees of freedom. A detector can be rotated independently around the centre of the chamber.

The samples were placed into the beam by a manipulator at 6° angle of incidence and the reflected radiation was measured at 12° exit angle after optimization of the tilt angle (to compensate for small mounting tolerances of each sample on the holder).

3. RESULTS

In order to estimate the thickness of silicon carbide coatings needed for low absorption of visible light and high reflectance in the VUV, we have made calculations using the optical constants given in the literature [1,2]. The results implied that a total absorptance of less than 0.1 (10 %), integrated over the entire spectral range, would be possible with SiC coating thicknesses below 20 nm, while sufficient VUV reflectivity would be obtained. The estimation has been confirmed by the measurements presented here.

3.1. Thermo-optical results

Using a photometer, the reflectance and the transmission of the samples was measured in the wavelength range between 200 nm and 1000 nm. The results are shown in Figure 1.

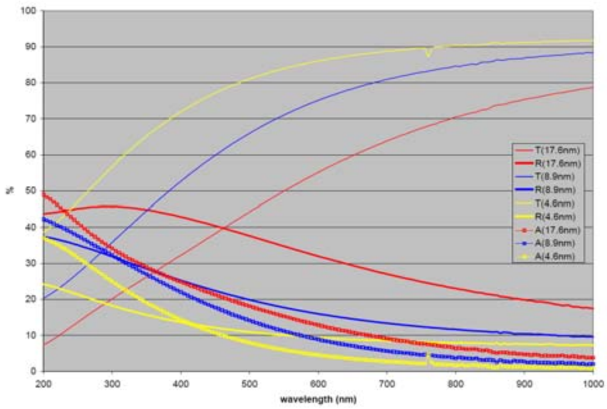

Figure 2: Results of reflectance (R) and transmission (T) measurements and calculated absorptance (A) of the SiC samples.

3.2. EUV reflectance results

At the four EUV wavelengths the reflectance of the samples was measured at 6° angle of incidence and compared with the SiC/CVD reference sample and with an uncoated quartz sample. The results are shown in Table 1.

Table 1: Reflectance results at the wavelengths 58.4 nm, 73.5 nm, 104.4 nm, 123.6 nm of the three SiC mirror samples #1, #2, and #3. Sample #0 is the SiC-CVD reference mirror, while "blank" refers to the uncoated quartz plate.

sample \ λ	58.4	73.5	104.4	123.6
#0 (SiC/CVD)	22	31	37	39
#1 (17.6 nm)	18	29	35	38
#2 (8.9 nm)	18	26	32	34
#3 (4.6 nm)	15	21	25	26
blank	4.3	5.4	3.3	4.7

The SiC coating of 8.9 nm already shows very good reflectivity, while the sample with 17.6 nm thickness already reaches very close to the reflectance of the SiC/CVD reference.

3.3. Thermo-optical properties under solar irradiation

The photometric data between 200 nm and 1000 nm of the silicon carbide coated mirrors have been used to calculate the thermo-optical properties under solar irradiation. The solar spectrum of the "Solar 2000 Model" [3] was used to calculate the transmission, reflectance, and absorption of the samples.

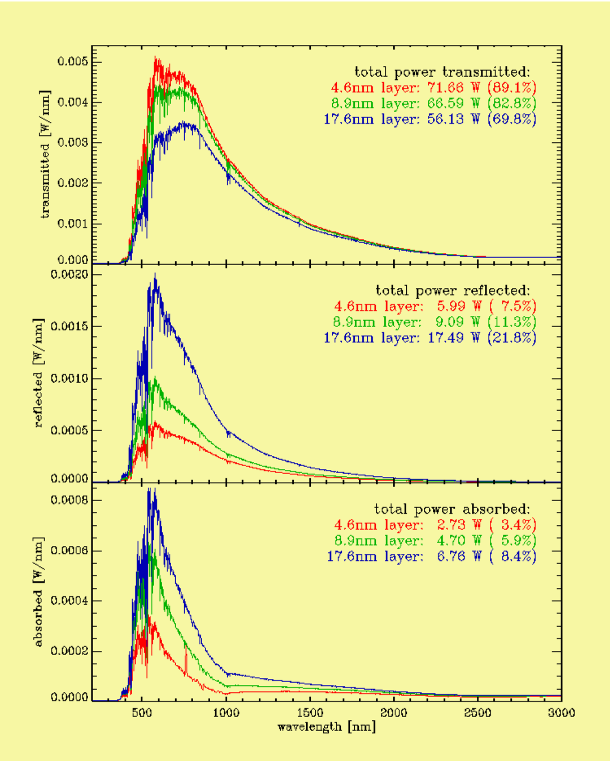

Figure 3: The transmission, reflectance, and absorption of the solar spectral irradiance of the three SiC mirror samples. The spectral curves were calculated from the measured photometric properties using the solar irradiance from the „Solar 2000 Model" spectrum of January 2000. The upper right corners of each panel show the absolute values of the total integrated power and the percentage (in parenthesis) of the solar spectrum

The results of this calculation are shown in Figure 3. The most important detail is the total power absorbed by the mirror from the solar spectrum (lower panel of Figure 3). In fact, the power absorbed by the SiC coating is quite moderate. Using the coating with a thickness of 8.9 nm, the power absorbed is less than 6 %. A conservative estimation, taking into account the residual absorption of quartz in the near infrared (above 1000 nm), may increase this value to not more than 8 %.

4. PROPOSED MIRROR DESIGN FOR A VUV/EUV SPECTROMETER

The results of this assessment are very promising in fulfilling the thermal requirements given by the Solar Orbiter mission. A spectrograph without entrance filter, where the primary mirror is directly exposed to the solar irradiation, can greatly benefit from this design using a mirror with low absorption of the solar spectrum. For a normal-incidence VUV spectrograph such an in-band reflecting mirror will provide the needed reflectance while absorbing only less than 8 % of the solar power. This will be of benefit for the Extreme Ultraviolet Spectrometer (EUS) of Solar Orbiter. In Figure 4 we show a possible heat rejection scheme for the primary mirror of a Gregory telescope design.

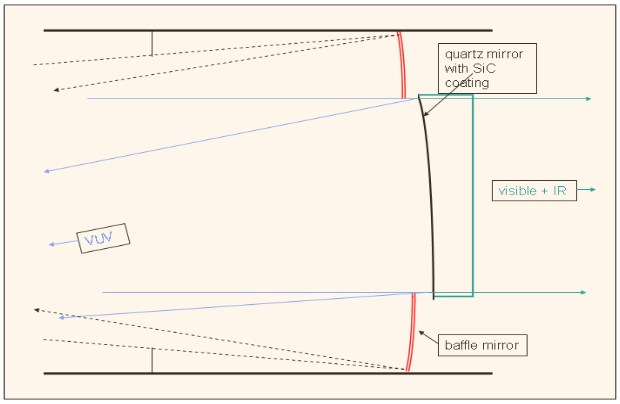

Figure 4: Proposed heat rejection scheme of the primary mirror of a VUV spectrograph using the thin SiC coating on a quartz mirror substrate.

Note that the rear surface of the mirror can be figured independently with optical power if needed. It can be coated with a reflective layer, to direct the heat back through the entrance aperture. This, however, would cause a double pass through the mirror with correspondingly higher total absorbed power. The better solution is an antireflective coating that minimizes reflection at the rear surface. In this way, most of the heat can escape through the mirror and be directed out to space.

While most of the near infrared and visible light is transmitted, about 12 % (cf. Figure 3 middle panel) of the heat will be reflected at the front surface of the mirror towards the focal plane. In a Gregory telescope design it is possible to collect all the light that is not in

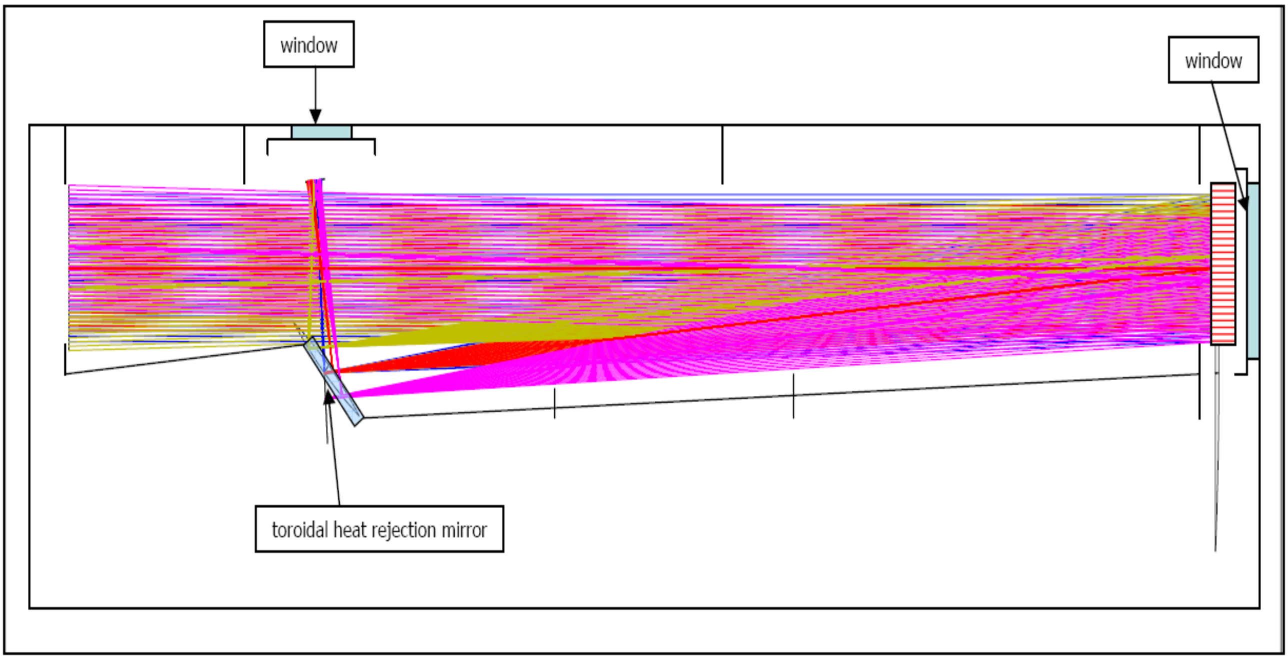

Figure 5: Proposed heat rejection scheme for the telescope section of the EUS instrument.

the field of view of the spectrograph just before the focal plane where the entrance slit is located. A toroidal mirror before the slit plane can be used to deflect the radiation that does not enter the slit towards a heat dump or, again, out to space. A possible scheme for such a design is shown in Figure 5.

5. CONCLUSIONS AND OUTLOOK

We have shown that a thin coating of silicon carbide on a transparent mirror can greatly reduce the amount of solar heat absorbed while reflecting vacuum ultraviolet radiation. A SiC coating with a thickness of 10 nm is a good compromise which almost achieves the high VUV reflectivity of bulk SiC-CVD mirrors while the total absorbed power from the solar spectrum is below 8 %. This result allows us to propose a heat rejection scheme for the Extreme Ultraviolet Spectrograph (EUS) for Solar Orbiter.

The heat rejection is most efficient if the radiation can be directed out to space, rather than collected for conduction to a space radiator. For Solar Orbiter in particular, the area for space radiators is limited and, thus, a goal is to minimize the radiator area needed for the instruments. The amount of heat entering the payload through the instrument's apertures can be reduced by such scheme if the visible and near infrared radiation can be rejected out to space.

Further experimental tests are necessary to optimize the coating's VUV reflectivity and visible transparency. Other materials are also possible. For instance, boron carbide coatings have similar reflectivity in the VUV [4], which is slightly better than SiC at wavelengths below 100 nm. Photometric measurements of such coatings will be made in the future.

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