VUV OPTICS DEVELOPMENT FOR THE ELETTRA STORAGE RING FEL

St. Günster, D. Ristau, Laser Zentrum Hannover e.V., Hannover, Germany,
A. Gatto, N. Kaiser, Fraunhofer-Institut für Angewandte Optik und Feinmechanik, Jena, Germany,
M. Trovò, M.B.Danailov, Sincrotrone Trieste, Trieste, Italy
F. Sarto, ENEA-Casaccia, Italy

Abstract

Vacuum ultraviolet optical components for the storage ring FEL at Elettra are under continuous development in the European research consortium EUFELE. Target of the project is the progress to shorter lasing wavelengths in the VUV spectral range. The current status allows lasing with oxide mirror systems down to 190 nm. The main obstacles for the development of optical coatings for shorter wavelengths is the high energetic background of the synchrotron radiation impinging onto the front mirror in the laser cavity. Investigations in single layer systems and multilayer stacks of oxide or fluoride materials demonstrate that fluoride mirrors reach highest reflectivity values down to 140 nm, and oxide coatings possess a satisfactory resistance against the high energetic background irradiation. However, pure oxide multilayer stacks exhibit significant absorption below 190 nm, and pure fluoride stacks suffer from strong degradation effects under synchrotron radiation. Possible solutions could be based on hybrid systems, combining fluoride stacks with oxide protection layers to provide high reflectivity and a robust behaviour under synchrotron radiation load.

INTRODUCTION

Dielectric mirror coatings for the vacuum ultraviolet (VUV , 120 – 195 nm) spectral range are deposited with physical vapour deposition methods from oxide and fluoride compounds. Their optical properties in respect to reflectivity, losses and stability are acceptable for applications in metrology systems, material processing and lithography applications. [4] Mirror coatings for the Free Electron Laser (FEL) were produced from oxide compounds which allowed a FEL lasing at the shortest wavelength of 189,9 nm at Elettra. [2,3] However, the mirror coating deposition for FEL lasing in the spectral range between 150 and 190 nm has to overcome severe obstacles. In this contribution the mirror development for the FEL at Elettra is summarised from the viewpoint of optical coating production. The work was performed in the framework of the European research project "Development of the European Free-Electron Laser at ELETTRA as a VUV Research Facility" (EUFELE).

PROBLEM

Mirrors for the Elettra FEL running in the VUV range below 190 nm should be provided. The laser cavity is embedded in the Elettra storage ring. Enclosed in the cavity a wiggler accelerates the electron, which generates finally photons for the FEL (Fig.1). The lasing wavelength is determined by the electron energy and the wiggler parameters (period and gap). The front mirror suffers the load of spontaneous synchrotron radiation that, besides the laser wavelength, contains also photons with energy up to the MeV range. Therefore the front mirror must be able to reflect the fundamental wavelength and to tolerate these high energy background photons.

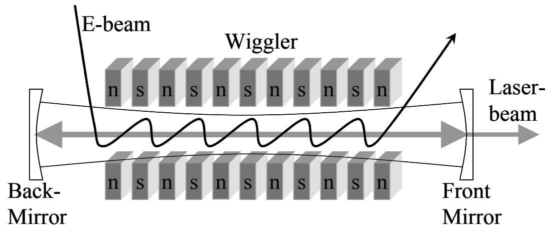

Fig. 1 : Configuration of a free electron laser resonator.

Laser action can be reached only if the amplification exceeds the optical losses, which in the case of FEL cavity are determined by the reflectivity of the two mirrors. While in the visible region losses due to absorption and scattering in the coating can be kept very low and are practically negligible, in the VUV range they have to be carefully considered and minimized. The tolerable minimum reflectivity for the SR-FEL at Elettra can be estimated to a value of 90 % for the front mirror, if the back mirror reflects above 95 %.

FEL systems are embedded in a vacuum environment (UHV). Residual molecules, especially hydrocarbon compounds, may lead to a surface contamination of optical components followed by a decrease of mirror reflectivity. In combination with VUV radiation and the chemical sensitivity of the coating material, this degradation effect can be amplified strongly.

DEVELOPMENT CONCEPT

Summarising the demands outlined before, suitable mirrors for the FEL laser system must provide a reflectivity above 95 %, they have to be able to withstand the high energetic background radiation, and they must be insensitive in respect to contamination effects. In the development phase suitable mirror materials were identified, different multilayer designs were developed, and complementary deposition methods were investigated. After coating deposition, the optical components were characterised in respect to their optical parameters. Then, the mirror coatings were irradiated at SR-FEL at Elettra. Finally, the components were inspected again and compared to the data gathered before irradiation. Single layer coatings were investigated in a similar procedure. Results were reported elsewhere [4].

EXPERIMENTAL

Deposition of optical coatings

Coating properties are determined by material selection and the employed deposition technique. For mirror systems down to the wavelength 190 nm, pure oxide or fluoride systems can be used. However, the material selection for the VUV spectral range is restricted by the band gap of most common deposition materials. Among the oxide materials, only SiO_2 with its low refractive index exhibits a negligible absorption down to 160 nm. Al_2O_3 as the potential high index material can be employed down to 190 nm. For shorter wavelengths only fluoride compounds are applicable. In this study SiO_2 and Al_2O_3 as oxide materials and MgF_2 as low refractive index material in conjunction with LaF_3 as high refractive index compound from the fluoride class were investigated.

Deposition techniques strongly influence the physical properties of the thin film. The aggregation of thin films depends strongly on the kinetic energy of the particles impinging on the substrate surface or an additional ion assistance. In order to provide a broad spectrum of film properties, deposition techniques with low kinetic energy of the aggregating particles and with high kinetic energy of the aggregating particles were employed: Thermal evaporation methods (E-Beam and boat evaporation), ion assisted deposition (IAD), plasma ion assisted deposition (PIAD) and ion beam sputter deposition (IBS).

Mirror designs were developed for the central wavelength 180 nm with maximum reflectivity as main target parameter. (See table 1) A standard fluoride quarterwave stack was used as reference system. This system was deposited by thermal evaporation, ion assisted deposition (IAD) and ion beam sputtering (IBS) deposition for comparison purposes. From the single layer investigations it was concluded that LaF_3 exhibits the strongest degradation in the FEL environment. Thus, a so called bi-stack system, with reduced LaF_3 content was deposited as a pure fluoride system also. Protected mirrors were designed using a SiO_2 top layer on a fluoride stack. For the SiO_2 protection layer E-Beam films and IBS films were compared. In addition, protection systems using a combination of Al_2O_3 and SiO_2 were deposited. Besides the fluoride stacks, a pure bi-stack oxide system, which was designed for the central wavelengths 187 nm, was deposited by IBS. For this mirror the Al_2O_3 layer thickness was minimised to reduce the effect of absorption.
All coatings were deposited on CaF_2 substrates.

Characterisation

Optical characterisation was performed before and after the irradiation experiment. VUV, VIS, and IR optical spectra were recorded for all samples. A VUV-spectrometer developed at the Laser Zentrum Hannover has been employed for the measurement of the spectral behaviour in the VUV-range [5]. Spectra in the uv-visible range and the MIR range were measured employing commercial spectrophotometers (λ900 and F1600 [Perkin Elmer]). Also, spatially resolving techniques were adapted and applied [6] for all spectrophotometric methods. Microscopic surface inspection was performed for the untreated substrates as well as for the irradiated samples. The samples were tested in irradiation experiments at SR-FEL at Elettra.

Table 1 : Overview of the deposited optical coatings.

Multilayer model coatings HR@180 nm	**Multilayer design**	**Employed deposition technique**			
Oxide Compounds		Boat	IAD	PIAD	IBS
Al_2O_3 / SiO_2 HR@187 nm	$(0.65\ H\ 1.35\ L)^{20}\ 0.65\ H$				**x**
Fluoride Compounds					
MgF_2 / LaF_3 HR@180 nm	$(H\ L)^{20}\ H$	**x**	**x**		**x**
MgF_2 / LaF_3 Bi-Stack HR@180 nm	$(0.7\ H\ 1.3\ L)^{20}\ 0.7\ H$	**x**			
Hybrid mirrors: Oxide and Fluoride					
MgF_2 [L1]/ LaF_3 [H2] SiO_2 [L2-E-Beam]	$(H1\ L1)^{20}\ H1$ + 6 L2 (SiO_2 Protection)	**x**			
MgF_2 [L1]/ LaF_3 [H1] Al_2O_3 [H2-IBS] / SIO_2 [L2-IBS]	$(H1\ L1)^{20}$ + H2 L2 H2 (Oxide Protection)	**x**			**x**
MgF_2 [L1]/ LaF_3 [H1] SIO_2 [L2-E-Beam] / SIO_2 [L3-IBS]	$(H1\ L1)^{20}\ H1$ + 1 L2 + 5 L3 (SiO_2 Protection)	**x**			**x**

Synchrotron and FEL Radiation Characteristics

In the free electron laser mode, Elettra runs in 4-bunch filling mode at relatively low energies (0.75-1.5 GeV), however, these specific FEL conditions are restricted to a few shifts per year. The number of tests would be insignificant. To increase the number of irradiation experiments, a configuration routinely adopted for user operation (multi-bunch, 2 GeV) was used as standard test condition. To reduce the high energetic background radiation, the synchrotron radiation load was restricted to bending magnet contributions. For the evaluation of the experimental results it has to be considered, that the irradiation stress under standard conditions is more severe than in the FEL mode.

RESULTS

Pure Oxide Coatings

Measurements on bi-stacks of the material pair Al_2O_3 and SiO_2 show that, even with an extreme thin Al_2O_3 layer thickness, the absorption of aluminium oxides is dominating the mirror performance. An adequate reflectivity can not be reached below 190 nm due to the absorption of Al_2O_3. Figure 3 illustrates this with the reflectivity spectra of three different coating runs targeted to three different central wavelengths. The reflectivity of the produced HR@187 nm was below 90 % at 180 nm.

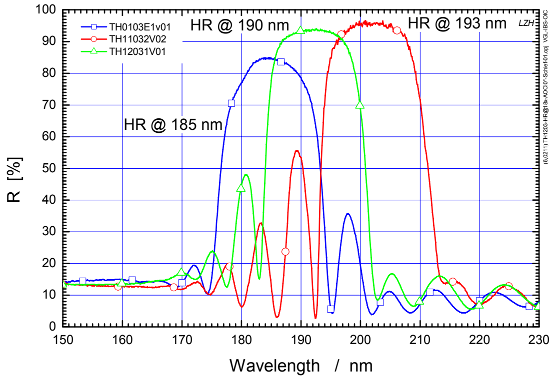

Fig. 2: Reflectivity of oxide Al_2O_3/SiO_2 deposited as bi-stack system [(0.65 H 1.35 L)20 0.65 H] for three different central wavelengths.

Pure Fluoride Coatings

Mirror system for the central wavelength 180 nm were deposited with different techniques. Multilayers produced by thermal evaporation and IAD deposition reach reflectivity values above 90 %. First results for IBS fluoride mirrors show, that a further process optimisation is essential. The results of the irradiation experiments on the conventional and the IAD mirror at Elettra display a strong degradation of reflectivity. Figure 3 and 4 present the behaviour for a bi-stack fluoride mirror deposited by thermal evaporation and for a standard mirror design produced by IAD, respectively. Both systems show strongest reflectivity degradation after irradiation. From additional measurements in the IR an intense hydro carbon contamination on the optics surface can be stated. The reflectance can be restored to approximately 90 % of the initial value of reflectivity with UV cleaning methods. A surface damage can not be observed by optical microscopy.

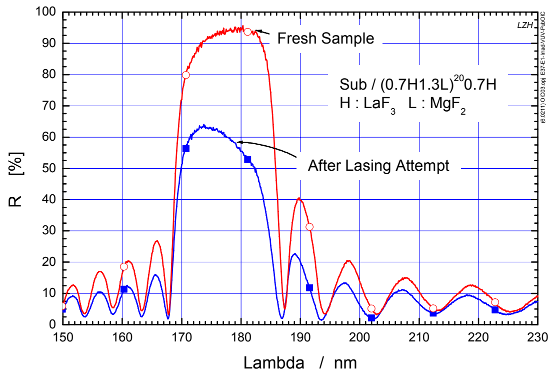

Fig. 3 : Reflectivity of fluoride bi-stack deposited by thermal evaporation before and after irradiation at SR-Elettra.

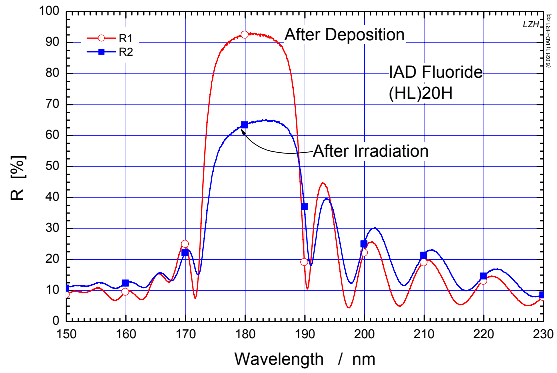

Fig. 4 : Reflectivity of a fluoride mirror deposited by ion assisted deposition (IAD) before and after irradiation at SR-Elettra.

Fluoride Coatings with Oxide Protection

Fluoride stacks, protected with SiO_2 single layers, could be produced with high reflectivity at 180 nm. However, the process concept has to be optimised to combine the fluoride and SiO_2 deposition. In particular, SiO_2 has to be deposited in a reactive O_2 atmosphere which may lead to an unwanted oxidation of the fluoride material. In addition, high energetic ions could create defects in the fluoride stack during the IBS process. After process optimisation, protected stacks with reflectivities above 95 % can now be realised.

The characterisation after SR-FEL irradiation reveals significant differences between the stacks protected with E-Beam SiO_2 and IBS SiO_2. Similar to the pure fluoride systems, the stack with E-Beam SiO_2 protection layer is strongly degrading in respect to its reflectivity (Fig. 5). In contrast, the stack with the IBS SiO_2 protection layer shows only a small decrease of reflectivity of about 2 - 4 %. (Fig. 6). With a mirror of this type stored emission in the FEL cavity was observed.

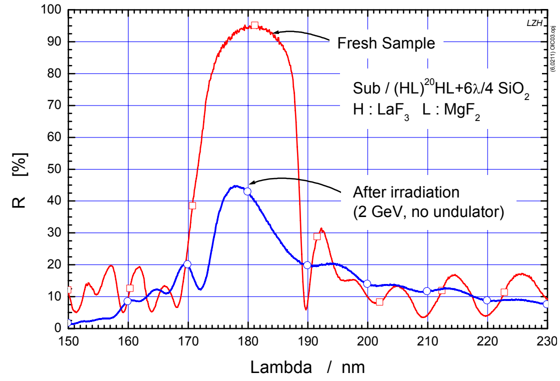

Fig. 5 : Reflectivity of a fluoride stack with E-Beam SiO_2 protection layer before and after irradiation at SR-Elettra.

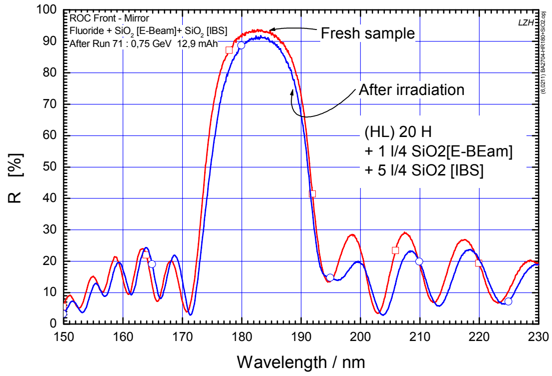

Fig. 6 : Reflectivity of a fluoride stack with IBS SiO_2 protection layer before and after irradiation at SR-Elettra.

Fluoride stacks protected with combinations of SiO_2 and Al_2O_3 did not achieve reflectivity values above 90 % at 180 nm. Further optimisation for this approach was terminated.

CONCLUSIONS

In the framework of this study optical materials for the production of VUV coatings were identified, adapted coating designs were developed and tested. Furthermore, the characteristics of selected deposition technique were studied. In the present stage, the protection of high reflecting fluoride stacks is considered as the major problem. Fluoride mirrors exhibit a high sensitivity for a hydro carbon contamination which causes a subsequent degradation of reflectivity in the FEL system. A clear improvement of robustness using ion assisted deposition technique, which produce film system with higher packing density, could not be observed until now. An adequate protection layer combination can be realised by an appropriate deposition of a dense SiO_2 layer on a fluoride stack. The structure of the sputtered SiO_2 layer seems to be much more effective for the protection of the fluoride surface, than the porous E-Beam SiO_2 layer. With optimised deposition cycle a reflectivity close to 99 % has been recently reached (Fig. 7). The FEL lasing test has to be performed.

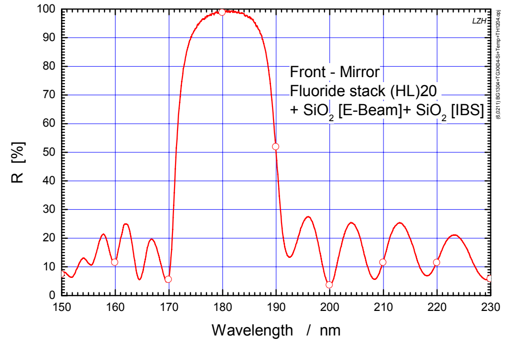

Fig. 7 : Reflectivity of an optimised fluoride stack with IBS SiO_2 protection layer after production.

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