The 8th International Conference on The Physics of X-Ray Multilayer Structures

12-16 March, 2006 **Sapporo, Japan**

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Presented at

The 8th International Conference on The Physics of X-Ray Multilayers Structures

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Invited Speakers

Rodolfo CUERNO
(Spain)
The physics of growth and ion erosion

Kazuhiro HAMAMOTO
(Japan)
Actinic EUV mask inspection of phase defect

Hans HERTZ
(Sweden)
X-ray microscopes with multilayer mirrors

Philippe JONNARD
(France)
X-ray spectroscopy and reflectomety study of interfaces of Mo/Si multilayers

Eva MAJKOVA
(Slovakia)
Sub-ps Laser patterning of multilayer Structures

Jörg MASER
(USA)
High-resolution X-ray diffractive optics

Michael James PIVOVAROFF
(USA)
Multilayer X-ray optics for biomedical imaging

Christian SCHANZER
(Switzerland)
Multilayer structures for neutron optical devices

Kazuhiko SOYAMA
(Japan)
Supermirror coatings for new neutron source

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Detailed Program

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08:50-09:30	Supermirror coatings for the new spallation source J-PARC	**Kazuhiko Soyama** (Invited talk)
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11:30-11:50	Developments in Metrology for Aperiodic Multilayers and their Applications	**Andrew Aquila**
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08:40-09:00	Towards laboratory soft X-ray microscopes based on reflective and diffractive optics and compact X-ray sources	**Igor A. Artyukov**
09:00-09:40	Multilayer X-ray optics for biomedical imaging	**Michael James Pivovaroff** (Invited talk)
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11:10-11:50	Compact X-ray microscopes with multilayer mirrors	**Hans Hertz** (Invited talk)
11:50	Closing remarks	
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Oral Sessions 1-9
Speakers' Abstracts

Multilayer structures for neutron optical devices

C. Schanzer, J. Stahn, M. Ay, J. Padiyath

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Neutron scattering, a technique complementary to e.g. light scattering, is an excellent tool to investigate structure and dynamics in condensed matter. Novel materials like GMR/CMR materials, biological samples or modern superconductors can often be grown only in small quantities. Since neutron experiments usually suffer from a lack of intensity of neutrons, measurements on small samples become difficult. In order to compensate for this, sophisticated neutron optics are desired to focus beams and to select a neutron spin state providing additional degrees of freedom for the experiment. Multilayers are an important element of advanced neutron optics because their properties can be widely tailored to account for specific demands.

In focusing devices, either linear tapered or with advanced geometries like parabolic and elliptic shapes, reflection angles become relatively large. Conventional neutron mirrors use the limited regime of total reflection from Ni films (θ_c = 0.1 - 1° for λ = 1 - 10 Å). In order to reflect neutrons at higher angles supermirrors have been proposed by Mezei [1]. Ni and Ti are dedicated materials for neutron supermirrors due to their large contrast in neutron scattering length density. These depth graded multilayers enable reflection angles *m* times of Ni films. State of the art are supermirrors with $m = 2$ and high reflectivity ($R > 0.9$) for neutron guides. Focusing devices usually require $m > 3$, which increases the number of layers drastically (typ. 1000 layers). Hence, interfacial roughness/interdiffusion and internal strain become crucial for the performance of the supermirrors, i.e. reducing the reflectivity and the stability of the supermirrors. Reduction of interfacial roughness and interdiffusion is achieved by reactive sputtering of Ni in an Ar:N_2 atmosphere resulting in significantly higher reflectivity. However, the reactive sputtering is accompanied by an increase of internal strain limiting the amount of N_2, which can be added, in particular for supermirror with large *m*, i.e. large number of layers. Alloys of Ni and Ti with small quantities of other materials are envisaged to modify the growth reducing internal strain while improving the interface quality.

A special property of Ni/Ti supermirrors is obtained when a small amount of Mo is added to Ni resulting in non-magnetic NiMo layers [2]. These mirrors can be employed to focus polarized neutron beams without depolarization. In another approach, defined interface gradients can be produced, e.g. a sinusoidal variation of the depth profile of scattering length density selects solely the first order superlattice Bragg peak without any higher orders. This solution represents a monochromator with high reflectivity and no contamination of higher orders.

Due to their magnetic moment, neutrons are sensitive to magnetic moments in matter making them a dedicated probe to investigate the magnetism of materials using polarized beams. On the contrary, this sensitivity is also employed to polarize neutron beams. Multilayers of proper combinations of materials (e.g. FeCoV/TiN, Fe/Si) have spin dependent reflectivities, i.e. for one neutron spin state nuclear plus magnetic scattering length density of the ferromagnetic material matches the nuclear scattering length density of the non-magnetic material. Hence, neutrons of this spin state do not “see” the interfaces and are transmitted while the opposite spin state is reflected. Such polarizing devices can be used in reflection or/and transmission mode and provide a beam polarization of > 95 %.

[1] F. Mezei, Communications on Physics **1** (1976) 81
[2] J. Padiyath, J. Stahn, P. Allenspach, M. Horisberger, P. Böni, Physica B **350** (2004) e237

Supermirror coatings for the new spallation source J-PARC

K. Soyama, R. Maruyama, D. Yamazaki and T. Ebisawa

Quantum Beam Science Directorate, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan

Neutron supermirrors have been utilized as reflective optical devices at many neutron sources for transporting, deflecting, focusing and polarizing neutron beam. Advanced neutron scattering instruments using supermirrors have been constructed in J-PARC, which will be the world's strongest pulsed neutron source, for research in condensed matter physics, chemistry, biology, material science, geology and engineering.

We have been developing the neutron supermirror using ion beam sputtering system, which enables us to produce good quality layers with high density and small grain size, because higher performance supermirrors bring us a considerable increase of the available neutron intensity. We have also investigated ion beam irradiation technique [1] to suppress the interface roughness, which is one of the most important problems in coating the supermirror with larger critical momentum transfer.

A new IBS coating system with a large effective deposition area of 500 mm in diameter has been installed for the production of neutron guides, benders, focusing mirrors and other optical devices using supermirrors with high reflectivity and large effective critical momentum transfer. It is equipped with dual bucket sources generating Ar+ ions. One is used for sputtering and the other is used for ion beam polishing.

The interaction of slow neutrons with an atomic nucleus is described by a scattering length b which has a characteristic value for each type of nucleus which is affected by nuclear resonances. Then, the Ni/Ti bilayer system is chosen for non-polarizing mirrors in many cases. To optimize film coating conditions, Ni/Ti multilayer monochromators and Ni/Ti supermirrors with m = 3, 4 were fabricated and measured their specular and off-specular reflectivities. The results indicate that the deposition rate distribution is homogeneous for the entire deposition area. The interface roughness is evaluated to be 0.6 nm. As a result of optimization, a Ni/Ti supermirror with m = 6.7 and the number of layers of 8000 has been fabricated successfully.

[1] K. Soyama, W. Ishiyama, K. Murakami, J. Phys. Chem. Solids. 60 No.8-9 (1999) 1587

Multilayer optic devices for neutron instruments

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Neutron supermirrors are being used more and more extensively at neutron sources in order to propagate neutron beams to the instruments, and to modify the beam properties before and after the sample under study. Due to the growing importance of polarised neutron techniques, which make them even more relevant to investigate in details the magnetic properties of materials, there is a strong demand for polarising and analysing optics for neutron instruments. A few issues that have to be faced while designing and producing multilayer optic devices, from the supermirror coating and characterisation to the final device, will be presented. A special emphasis will be put on supermirror polarisers and analysers, through a few examples of recent developments achieved at the ILL in Grenoble.

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Actinic EUV mask inspection of phase defect inside a multilayer

K. Hamamoto[1,4], Y. Tanaka[1,4], T. Yoshizumi[1,4], N. Sakaya[2,4], M. Hosoya[2,4], T. Shoki[2,4], N. Hosokawa[3,4], T. Watanabe[1,4] and H. Kinoshita[1,4]

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Extreme ultraviolet lithography (EUVL) will introduce as next generation lithography of 32 nm node in 2009. Defect-free mask fabrication is one of the critical issues to lead EUVL. There are two types of defects in EUVL mask: amplitude defect such as particle and phase defect inside multilayer. However, phase defect due to the multilayer fabrication cannot be resolved with an commercially inspection tool using VUV light. So, we constructed the EUV microscope for at-wavelength mask inspection which consists of Schwarzschild optics (NA0.3, 30X) and X-ray zooming tube.

Using this microscope, the image of the programmed phase defect that was produced on a grass substrate was observed. Figure 1 shows the EUV image of programmed defect of 90 nm wide and 5 nm high. EUV light illuminate and penetrate in Mo/Si multilayer. However, the multilayer on the upper part of programmed defect is disarranged, so the incident light does not reflect according to the Bragg's equation. These reflected light is collected by Schwarzschild optics and imaged on X-ray zooming tube as shown in Fig. 2.

As described above, we succeeded in observation of the topological defect image inside a multilayer using the EUV microscope.

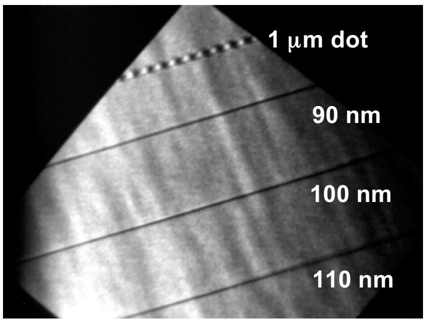

Fig. 1 EUVM image of a programmed phase defect.

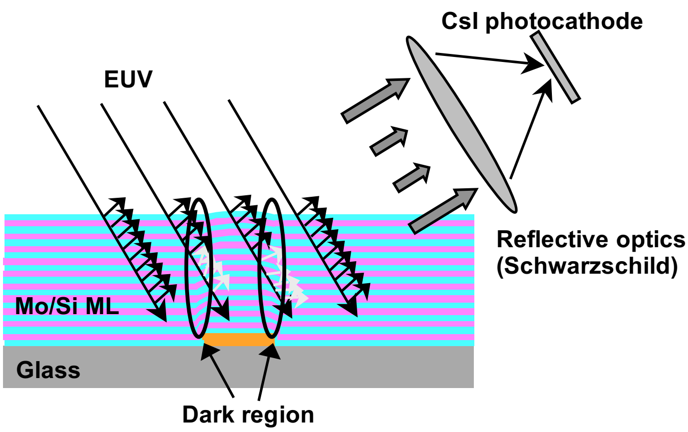

Fig. 2 Mechanism of a phase defect inspection.

Interface-engineered multilayer mirrors

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Presentation preference: oral

Most applications of Mo/Si multilayer optics require a high normal incidence reflectivity. Using dc magnetron sputtering we achieved R = 68.8 % @ λ= 13.5 nm. Different interface-engineered Mo/X/Si/X multilayers with maximum reflectivity of 69.6 % at 13.5 nm were developed (Fig. 1). These new multilayer mirrors consist of molybdenum and silicon layers separated by different interdiffusion barriers (X). Microstructure and optical properties of the multilayers have been investigated by small and large angle Cu-Kαscattering, HRTEM and characterized by EUV reflectometry. A conception of interface-engineered design for optical properties enhancement of short-periodic multilayer mirrors is discussed.

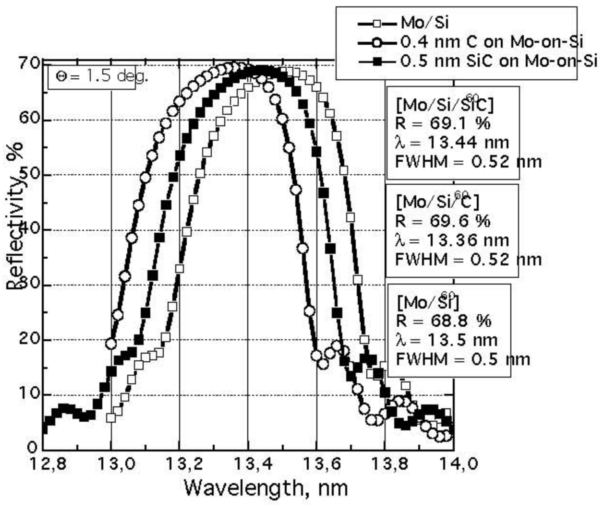

Fig. 1

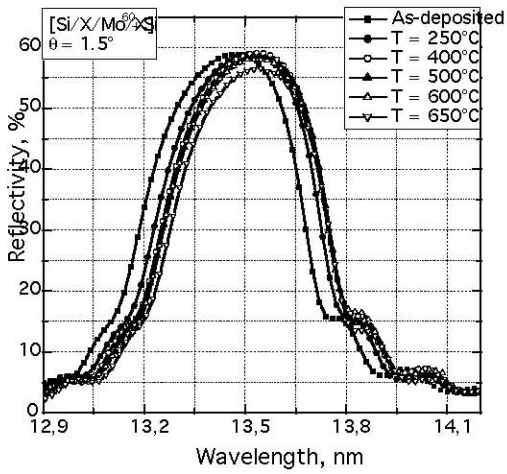

Fig. 2

Some applications of multilayer mirrors require not only the highest possible normal incidence reflectivity but also a long-term and thermal stability at the operating temperatures. A serious problem of Mo/Si multilayers is the instability of reflectivity and peak wavelength under high heat and radiation loads. The instability of Mo/Si multilayers becomes especially critical at elevated temperatures of more than 200°C. Investigations on new high-temperature multilayers were focused on new interface-engineered Mo/X/Si/X systems (Fig. 2). The multilayer designs as well as the deposition parameters of the systems were optimized in terms of high peak reflectivity at a wavelength near 13.5 nm (Rp ≥60.0 %) and a broad operated temperature range (T = 20 -650°C). Annealing in vacuum was carried out at elevated temperatures up to 700°C for up to 100 hours. The major results of the comparative study will be presented in this paper.

X-Ray Multilayer Coating Technology for Extreme Ultraviolet Lithography Tools

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Extreme Ultraviolet Lithography (EUVL) is the most promising candidate as the next generation lithography (NGL) to be used for the manufacturing semiconductor devices with 32nm node and below. Full-field EUV alpha exposure tool will soon be launched. EUVL is based upon x-ray multilayer coating technology. Nikon has started R&D of x-ray multilayer coatings ever since 1980's. We have conducted R&D of EUVL based on the x-ray multilayer coating technology. Basic EUV exposure research using Schwarzschild optics was conducted in SORTEC[1)]. We have also developed a high-numerical aperture (NA) and small-field EUV exposure experimental system (HiNA), which is now being operated at ASET Atsugi laboratory[2)]. All these have accelerated the EUVL technology, as well as led to some other applications of x-ray multilayer coatings, such as x-ray telescopes and neutron reflection mirrors[3, 4)]. Now we are concentrated on the development of multilayer coating technology for EUV alpha exposure tools. The following are some key issues of multilayer coating technology for EUVL.

High reflectivity
Low internal stress
Graded coating
Capping layer
Scale up to large mirrors

We are using ion-beam sputtering and low-pressure magnetron sputtering for the deposition of Mo/Si multilayer coating for EUV optics. By using Xe instead of Ar for sputtering gas in low-pressure magnetron sputtering, an increased high reflectivity up to 70% in the wavelength region around 13nm has been attained[5)]. Mo/Si multilayer coatings deposited with sputtering usually have certain amount of compressive stress, which is large enough to deform the precisely polished mirrors. Therefore stress control technology is required. We have developed stress control technique using stress compensation layers, thereafter we are able to control the internal stress freely[6)]. To obtain the graded coatings, we are using the fixed deposition mask with the rotating substrate. New technology for graded coatings using a moving deposition shutter (MDS) has also been developed. Capping layers are surface protecting layer to prevent Mo/Si multilayer coatings from surface contamination with carbon or surface oxidization. We are now searching the optimized materials for the capping layers through the EUV exposure experiments with several material candidates. In the manufacture of projection optics for EUV alpha exposure tools, multilayer coating technology for large mirrors with the diameter of over 500mm is required. We have installed a new low-pressure magnetron sputtering system for large substrates with the maximum diameter of 600mm. Now preparation of multilayer coating technology for EUVL exposure tools has been completed.

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4. K. Soyama, et al., J. Physics and Chemistry of Solids, **60**, 1587 (1999).
5. M. Shiraishi, et al., Proc. SPIE, **5037**, 249 (2003).
6 M. Shiraihsi, et al., Proc SPIE, **5374**, 104 (2004).

Phase transitions at enhanced temperatures in Mo/Si multilayers

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Mo/Si multilayers, with layer thicknesses of 3-5 nm, are currently being developed as reflective coatings for the optics of Extreme Ultraviolet Lithography (EUVL) systems. Such optics require high thermal stability to resist structural changes under extremely high photon fluxes. The stability of Mo/Si multilayers was investigated by a sequential annealing treatment. The changes at Mo/Si interfaces were determined by grazing angle and wide angle X-ray diffraction (XRD). A detailed analysis of structural changes at Mo/Si interfaces is presented for multilayers with Mo ratios in a period (Γ) in the range 0.1-0.8. The multilayer thickness decreases during annealing due to additional intermixing of bulk constituents at interfaces. For all multilayers that still contain bulk Mo and Si, a phase transition occurs at temperatures higher than 330°C. The activation energy and interdiffusion coefficient at this temperature indicate the diffusion of Si into a Mo_xSi_y compound[1]. We present results that clearly identify the recrystallization of the multilayer during the phase transition.
The thermal stability can be improved by using diffusion barriers at Mo/Si interfaces. Using carbon as a diffusion barrier, we show that the phase transition can be postponed towards much higher temperatures, increasing the thermal stability.

1. Rosen et al, Applied Optics, 32, no. 34, 6975-6980 (1993):

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X-ray spectroscopic and reflectometric study of the interfaces of Mo/Si multilayer interferential mirrors

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We present the study of Mo/Si multilayers interferential mirrors (MIM) with a Si thickness of 2 nm and a Mo thickness varying from 1 to 4 nm. The physico-chemical analysis of the interfaces within the MIM is carried out by x-ray emission spectroscopy (XES) induced by electrons. The Si 3p density of valence states of the silicon atoms present in the multilayers are obtained via the analysis of the band Si Kβ (3p→1s transition) emission band. From the shape of this emission band, the silicides present at the interfaces are identified ($MoSi_2$ and Mo_5Si_3) and their thickness determined. The characteristics of the interfaces are used to describe a period of the MIM by a four layers model. This model and the rms roughness deduced from the x-ray reflectivity (XR) measurements performed at 0.154 nm are then introduced in the simulations of the experimental XR curves obtained at several wavelengths in the soft x-ray range (0.712, 1.33 and 3.16 nm). This procedure enables us to evidence an increase of the performances of the studied MIM when the thickness of the Mo layer goes from 2 to 3 nm. This is due to the percolation of the Mo film at this critical thickness. The interpretation given by the combination of the non-destructive XES and XR methods is confirmed by destructive methods such as secondary ion mass spectrometry and cross sectional transmission electron microscopy.

Exact Determination of the Phase in Time-Resolved X-Ray Reflectometry

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We discuss a new and accurate method of solving the phase retrieval problem found in X-ray reflectometry. The approach is applicable to the characterization of thin films whose X-ray reflectivity can be measured *in-situ* during growth. Since the chemical composition of the incoming flux of particles generating the layer deposition may vary with time, the dielectric permeability of the film changes with depth. By measuring the reflectivity *in-situ* as a function of the time t, both the reflectivity R(t) and the derivative dR/dt are known. Hence, both the real Re[r(t)] and the imaginary Im[r(t)] parts of the amplitude reflectivity r(t) can be found exactly, in a very simple manner and following an explicit analytical form.

During the time interval necessary to measure the derivative dR/dt, we postulate that the composition of the film material located underneath remains unchanged. This is obviously valid at certain stages of the growth and not valid at others, e.g., in case of implantation or diffusion of atoms when several materials are present. Because the method assumes proportionality between the polarizability ε-1 and the density of the material, it can be applied to X-ray or neutron reflectometry but cannot be used with visible light. In addition, we demonstrate that having access to the temporal dependence of the reflectivity R(t) at a fixed grazing angle θ, it is possible to infer the depth-distribution of the dielectric constant $\varepsilon(z)$.

First experiments on the exact phase retrieval are discussed. The measurements were performed at the beamline BM5 of the ESRF. A special vacuum chamber intended for the sputter deposition of materials was installed at the beamline allowing to measure *in-situ* and in real-time both reflectance and scattering from a growing film [1]. A comparison of two methods of reconstruction of the dielectric constant profile is presented. The first one applies the exact phase retrieval method on the temporal dependence of the reflectivity R(t) measured at a fixed grazing angle θ of the probe beam. The second one solves the inverse problem of reflectometry, as described in [2], using angular-dependent reflectivity data R(θ) measured at fixed film thickness (after deposition). A good agreement between the two methods was obtained.

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Phase change observation of EUV reflection multilayer by total electron yield and reflection spectra

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In the extreme ultraviolet (EUV) wavelength region, normal incidence mirrors were made available through the use of reflection multilayers and are required to have extremely low aberrations[1]. To achieve low aberrations of reflection multilayer mirrors, the technique of surface milling has been proposed as an accurate correction method of figure errors[2]. In order to make an accurate correction however, it is important to first obtain information regarding the reflection phase in multilayer mirrors.

Total electron yield (TEY) intensity is optically represented by three terms: absorption-, reflection-, and interference- terms[3]. TEY intensity of reflection multilayers is approximately represented by a simple phase term, which is included in the interference term. When the attenuation length L of emitted photoelectrons from the top layer is smaller enough than the thickness d of the top layer, the interference term of TEY intensity $I_{TEY}(\lambda)$ is represented by

$$I_{TEY}(\lambda) = I(\lambda)\ (\ 1 + R^2 + 2\ R\ \mathbf{cos}(\delta - 2\xi d - 2\xi L)\ ), \qquad (1)$$

where $I(\lambda)$ is a TEY spectrum of the top layer, R is the real part of the complex reflectance of the top layer, δ is the reflection phase at one layer below the top layer, and ξ is the real part of the top-layer's propagation-vector using angle of incidence θ and complex dielectric functions, ε and ε_v, of the top layer and the vacuum, respectively.

In this study, [Mo 2.6nm/Si 4.1nm]×20 multilayers with different thicknesses of top Mo layer were fabricated on a same Si substrate. Thicknesses of the top Mo layer were accurately controlled by the shutter that was placed in front of the sample, and were deposited from 0.4nm to 3.2nm at 0.4nm intervals. TEY spectra of these aperiodic multilayers were measured with reflection spectra. Obtained TEY spectra showed that peak-positions changed as the increase of the film thickness of the top Mo layer. These TEY spectral changes give the phase change on reflection according to the Eq. (1). In Figure 1, phase changes obtained experimentally are represented with those obtained numerically using the exact formula[3]. Experimental phase changes are reproduced well by the numerical simulations. This result suggests that the changes of reflection phase δ will be also observed by both reflection and TEY spectra.

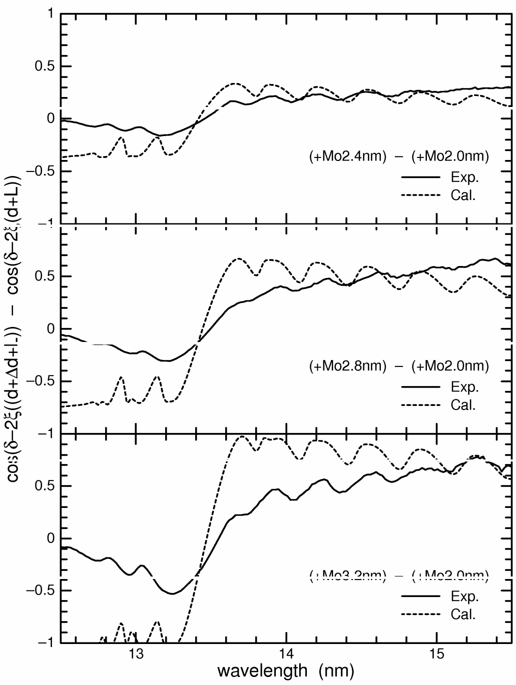

Figure 1: The **cos** term in the interference term of Eq. (1). Solid curves represent the experimental results and broken curves, the calculation ones.

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Multilayer deposition and calibration for SWAP EUV off-axis telescope

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SWAP (**S**un **W**atcher using **A**ctive Pixel System detector and imaging **P**rocessing) is a solar EUV imager that has been selected to fly in 2007 on the PROBA-II technological mission of the European Space Agency (ESA). SWAP will provide solar corona images in the Fe IX/X line (λ=17.5 nm) and will complement the observations provided by SOHO-EIT and STEREO-SECCHI instruments. SWAP is equipped with a specifically EUV enhanced CMOS APS detector and a dedicated electronics module for on-board data processing [1]. It will prepare the technological developments for the future EUV imagers of Solar Orbiter, the next outstanding ESA solar mission [2].

The EUV optical design of SWAP is based on a Ritchey Chretien off-axis system. The primary mirror shape is close to spherical and is tilted along the off-axis plane to compensate for aberrations. The secondary mirror is spherical. Each mirror is made of zerodur and is composed by a cylindrical main core and a cylindrical tail for bonding with mechanical cells. The surface of the mirrors was polished down to a roughness lower than 0.5 nm. The performance requirements in the EUV spectral range for the multilayer coatings are a peak wavelength of 17.5 nm +/-0.2 nm, a bandwidth lower than 1.8 nm and a peak reflectivity higher than 35%.

Mo/Si multilayers have been deposited in a high vacuum chamber equipped with a hollow cathode gun and a neutralizer working with Ar and Ar/10%H2 gases. The ion beam sputtering process developed for the EUVI 4-channels telescopes of the STEREO-SECCHI instrument [3] was used for the SWAP multilayer coating process An identical multilayer was deposited on each of the SWAP primary M1 and secondary M2 mirrors (flight and spare sets) which were preliminarily bonded on their mechanical mounts. A mask was designed and mounted in the deposition chamber in front of the substrate in order to reach a thickness uniformity lower than 1% on the total area of the mirrors. Simulations predicted that no lateral gradient of thickness was needed to compensate the angular incidence variation on the mirror surface. However, the multilayers were optimized for the mean incident angle, slightly biased from the normal incidence.

The deposition rate and thickness were controlled by using of a quartz microbalance during the process. In order to adjust the wavelength selection of the Mo/Si coatings, calibration samples and witness samples were deposited and characterized for each flight and spare M1 and M2 mirrors respectively. For each sample the multilayer spacings were deduced from grazing angle X-ray reflectometry @ 0.154 nm. The at-wavelength reflectivity was measured on the PTB synchrotron facility (Berlin)for calibration samples, and on the EUV reflectometer at CEMOX (Centrale d'Elaboration et de Métrologie des Optiques X - Orsay) operating with a plasma laser source for calibration and witness samples. A cross-analysis of the data provided by both methods compared to additional measurements done on the BEAR line of the ELETTRA synchrotron facility (Trieste) allows to conclude that the performances requirements have been satisfied for each of the 4 mirrors. The operating conditions of the EUV CEMOX reflectometer optimized for this purpose are described.

This work was performed thanks to the financial support of the Belgian Federal Science Policy Office (BELSPO), through the Belgium ESA/PRODEX program.

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Development of thin foil nested hard X-ray telescope

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X-ray telescope plays very important role in X-ray astrophysics. It requires high through put for sensitivity of observation. In this point of view, multi-nested thin foil optics(Seremitsos, 1996) is very suitable for astronomical use.

We have developed high through put hard X-ray telescope using depth graded multilayer X-ray mirrors for balloon borne experiment. Thin foil X-ray mirror is key of high through put optics. Replicated mirrors are developed for thin foil optics, it actually used in X-ray telescopes on-board XMM-Newton and Suzaku satellite.

In these telescopes, mirror surface is gold single layer using total reflection. On the other hand, multi layer must be needed as X-ray mirror for hard X-ray telescope.

In our hard X-ray telescope, multilayer is deposited on the smooth surface of glass mandrel, then replicated on to thin aluminum foil using epoxy. Thickness of aluminum foil is 200 μm. In the case, 8m focal length and 40 cm diameter, aperture efficiency is about 60%.

Pre-flight calibration of the telescope at synchrotron radiation facility SPring-8/BL20B2. Measurement at BL20B2 has great advantages such as extremely high flux, large size and less divergent beam. Monochromatized X-ray covering entire hard X-ray region, from 8 keV to over 100 keV. Detailed measurements using SPring-8 reveal that the image degradation of the individual mirrors is most effective to the spatial resolution of the telescope.

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Growth, Structure and Performance of Pt/Co X-ray Multilayers

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ABSTRACT

We describe our recent investigations of the growth and characterization of X-ray multilayer structures for use in astronomical instrumentation. Our goal is to develop short-period X-ray multilayers that work at normal incidence in the soft X-ray region. Specifically, we want to develop imaging systems that can be tuned to lines such as O VII (2.2 nm), O VIII (1.9 nm), and Fe XVII *3s-2p* (1.7 nm) and *3d-2p* (1.5 nm), for both astronomical and solar applications. This spectral region can now only be imaged using grazing incidence optics, which are intrinsically broadband. For solar physics in particular, the Fe XVII lines are extremely important, since they represent the primary emission for active regions ($3\text{-}5\cdot 10^6$ K) and can not be observed in the EUV where efficient normal incidence mirrors now operate.

In this work Pt/Co multilayer structures were synthesized in a dual-target DC magnetron sputtering system. The multilayers were designed with a period of Λ=0.855 nm and a layer thickness ratio of Γ=0.37 for normal-incidence reflection of the 1.7 nm wavelength (Fe XVII *3s-2p*).

During DC magnetron sputtering, it can be expected that the energetic particles present in the plasma will have large effects on the surface of the growing film. For maximum reflectivity sharp and abrupt interfaces are essential; a demand that increases exponentially with decreasing multilayer period. We have investigated growth techniques designed to control the deposition energetics, in order to produce optimally smooth and sharp interfaces, thereby leading to maximum reflectivity performance.

A low substrate temperature and no energetic particle irradiation during growth minimizes bulk diffusion and interface mixing. However, such conditions may lead to a kinematically limited growth with an increased and accumulated roughness as a consequence. In this work varying sputtering gas pressures (p=2, 5 mTorr) and sputtering gases (Ar, Kr) have been used in order to study the effect of un-intentional energetic particle irradiation. In addition, intentional irradiation varying from 21 eV electron bombardment to 81 eV ion bombardment, have been utilized in order to stimulate the ad-atom mobility and improve the interface flatness. The optimal irradiation energies will be discussed in view of surface and bulk displacement energies of the constituting layer materials. The interfacial structure was investigated using hard X-ray specular reflectivity and diffuse scattering and soft X-ray at-wavelength reflectivity together with IMD simulations of these.

Dynamical TRIM simulations combined with calculations of the gas-phase collisions have been made to obtain the number and energy distributions of energetic particles in the substrate vicinity. It is found that backscattered neutral sputtering gas atoms have energies ranging up to about 200 eV at the sputtering conditions used. The experimental results are discussed and compared with dynamic simulations using the TRIM code.

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Design and fabrication of multilayer polarizers working in wide spectral and angular ranges for EUV and soft X-rays in IPOE

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Abstract: This report introduced the recent development of the non-period multilayer polarizers working in wide spectral and angular range for EUV and soft X-rays in Institute of Precision Optical Engineering, Tongji University, including design, fabrication and measurement. The main feature of our design method is the use of non-periodic multilayer and the use of an analytical solution as a starting point for direct computer calculation. The technique, based on a combination of analytical and numerical methods, solves the inverse problem to give the composition profile of a non-periodic multilayer coating. The Mo/Si multilayer polarizers were designed and fabricated using the ultrahigh vacuum DC magnetron sputtering in IPOE, and measured at BESSY-II (shown in Figs.1 and 2). The measured s-polarized reflectivity is 27% at 13.1 nm and higher than 15% over the wavelength range of 13~19 nm. Nearly constant s-reflectivity, up to 37%, is observed over the 15~17 nm wavelength range, where the degree of polarization is more than 98% (Fig. 1). Furthermore, these multilayer polarizers also show high s-reflectivity and polarization over a broad angular range at fixed wavelength (Fig. 2). These multilayer polarizers working in broad spectral and angular range will greatly simplify experimental arrangements.

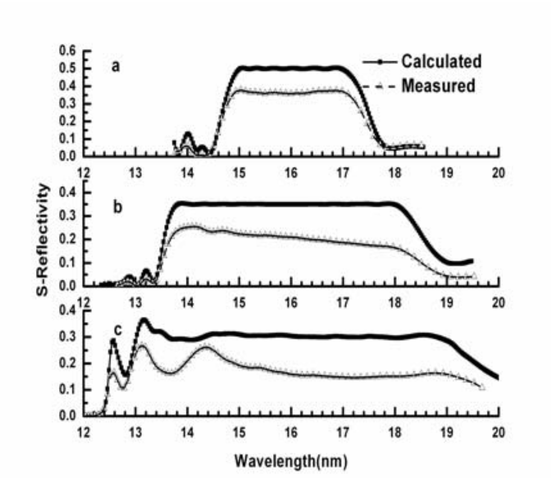

Fig. 1. Measurement results of Mo/Si multilayer polarizers working in broad spectral width at the grazing incident angle of 50°.

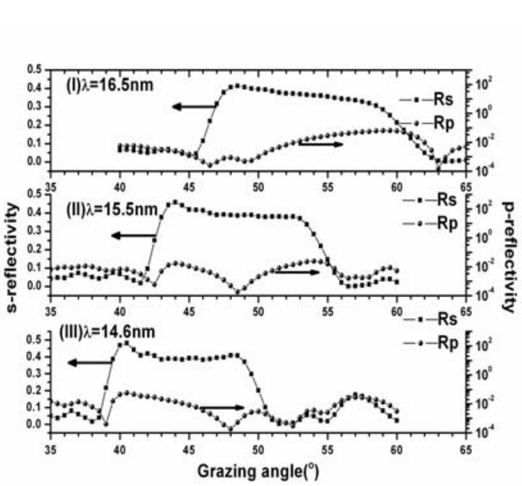

Fig. 2. Measurement results of Mo/Si multilayer polarizers working in wide angular range at fixed wavelengths of 16.5 nm, 15.5 nm and 14.6 nm.

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Developments in Metrology for Aperiodic Multilayers and their Applications

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Aperiodic multilayers have been designed for various applications, using numeric algorithms and analytical solutions, for many years with varying levels of success[1,2,3]. This work developed a more realistic model for simulating aperiodic Mo/Si multilayers to be used in these algorithms. Using a genetic computer code[4] we were able to optimize a 45° multilayer for a large bandpass reflection multilayer that gave good agreement with the model.

Aperiodic multilayers have also been discussed in applications for pulse compression of ultra short EUV/soft x-ray pulses[5,6]. Controlling the reflected phase of the multilayer structure preforms the pulse compression, however it is difficult to measure the reflected phase of these multilayers. This work demonstrates a method of using photocurrent to measure the electric field at the surface of the multilayer. This electric field correlates directly to the reflected phase of the multilayer through the standing wave formed in the structure.

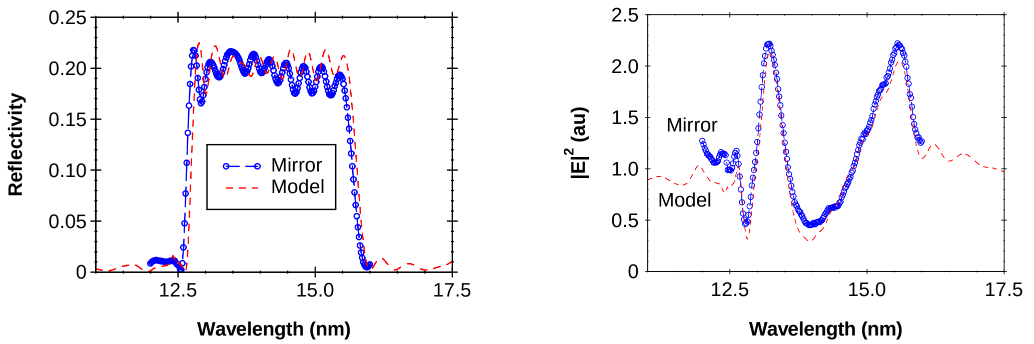

Fig. 1&2 : The reflectivity measurement for a 45° Mo/Si aperiodic multilayer mirror and the corresponding surface electric field ($|E|^2$). These graphs show the good agreement with the model for the mirror.

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Design and fabrication of X-ray supermirrors in IPOE

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Abstract: Hard x-ray applications that could benefit from X-ray supermirror include focusing and imaging instruments for astronomy physics, collimating and focusing devices for synchrotron radiation, and particle filtering in plasma diagnostics. This article reports the main results of our recent work including the design, fabrication and testing of the X-ray supermirrors.

Three methods to design the supermirrors at hard X-ray region were introduced, including Simplex Optimization (SO), the Stimulating Annealing (SA) and the method proposed by Igor (IG). All of the three methods were used to design the broad angle response supermirrors. Using the methods of SO and IG, the supermirrors with broad photon energy band were designed and optimized. The Nevot-Croce model is used to describe the negative effect due to the interfacial roughness and diffusion in supermirrors. These supermirrors were all fabricated using a high-vacuum DC magnetron sputtering. W/B_4C and W/Si multilayer supermirrors were deposited on polished silicon substrates in the base pressure of about 10^{-4} Pa using the argon (purity 99.995%) as working gas in the pressure of 0.4 Pa. These broad angle response supermirrors were measured by the X-ray (0.154 nm, the K_α line of Cu) diffractometer (XRD) at Shubnikov Institute of Crystallography, Russia. The measured reflectivity of W/B_4C supermirror is 23% in grazing angle region of 0.9~1.2°. The measured reflectivity of W/Si supermirror is 30% and 18% in the grazing angle regions of 0.4~0.85° and 0.75~1.1°, respectively. The W/Si supermirrors with broad photon energy band were also designed and measured at Nagoya University, Japan. The measured reflectivity is 20~23% in the energy region of 20-30 keV.

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Multilayer Laue Lenses - a Path towards Nanometer Focusing of X-rays

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High-resolution diffractive Optics have proven a spatial resolution of 15 nm [1] in the soft x-ray range, and of below 50 nm in the hard x-ray range [2]. A challenge to reaching high diffraction efficiency and high resolution in the hard x-ray range has been manufacture of diffractive structures with high aspect ratios.

We have developed a new approach towards manufacture of hard x-ray optics, the “Multilayer Laue Lens” (MLL). MLL’s are fabricated by coating a flat substrate with alternating layers of nanometer thickness, with d-spacing varying to form the zones of a linear zone plate. Thin cross sections of the multilayer are then made, which focus x-rays when illuminated in transmission (Laue) diffraction geometry. Crossing two such linear zone plate sections will allow 2-dimensional focusing.

We have studied the diffraction and focusing properties of MLL’s theoretically, and shown that a resolution limit of 5 nm can be reached using a non-optimized geometry, and a resolution limit approaching 1 nm using an optimized geometry [3,4]. We have also demonstrated a line focus with a width of 30 nm at a photon energy of 19.5 keV, with a diffraction efficiency of 44%.

We will discuss the diffraction properties of diffractive optics in general, of MLL’s in particular, and show recent results.

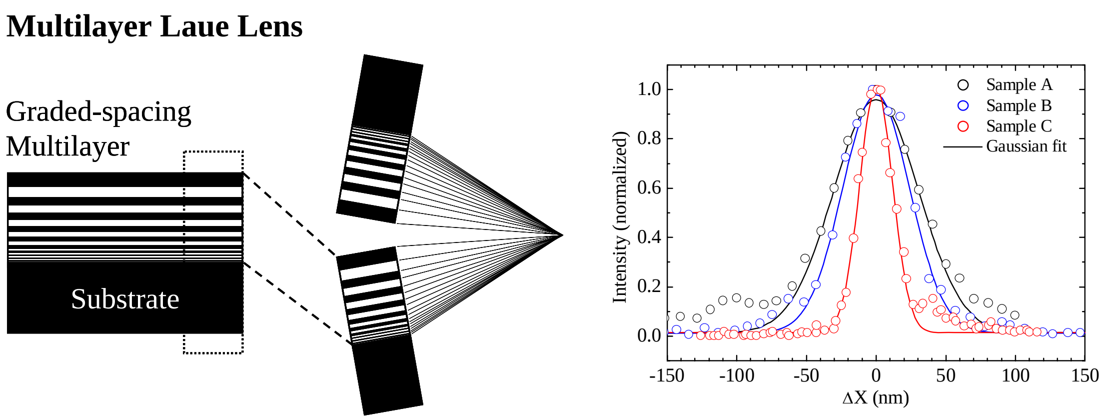
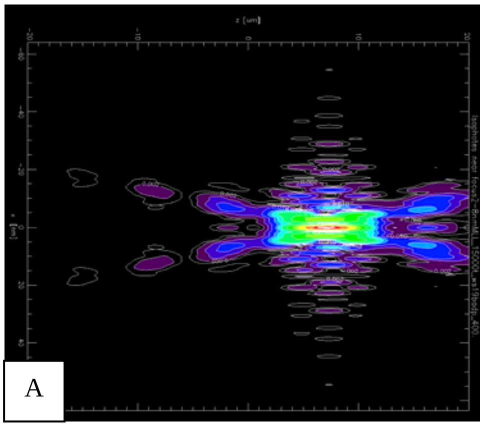


Fig. 1: Geometry of an MLL, and line focus obtained with different MLL structures



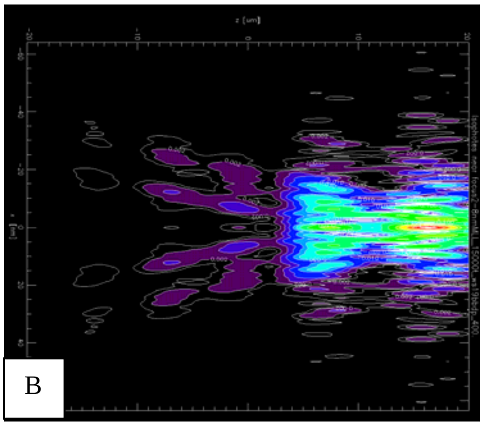


Fig. 2: Isophotes of an ideal (A) and an unoptimized (B) Multilayer Laue Lens with an outermost zone width of 2 nm. In the ideal case, a spatial resolution of 2 nm is achieved.

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Towards laboratory soft X-ray microscopes based on reflective and diffractive optics and compact X-ray sources

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The review describes rapid progress in soft X-ray imaging and microscopy obtained in the spectral regions 13.9-46.9 nm and 4.5-5.0 nm for the last two-three years.

The creation of bright EUV laser sources working at wavelengths 13.9-46.9 nm made possible to perform imaging experiments in both transmissive and reflective modes that greatly increased a number of objects for study. Additional advantages for imaging arise from a high sensitivity of reflection and transmission in this spectral region to impurities, contamination and the modification of the surface. At present the spatial resolution about 100 nm is obtained with an experimental set-up, which includes a laboratory EUV laser, Sc/Si multilayer optics and Fresnel zone plates. We present our experimental results that show the state-of-art in this field and discuss the ways of further progress. There are good promises for the development of practical and readily available nanoimaging tools working in quasi-real time at rate mainly limited by the readout of CCD detectors.

New opportunities were found in so-called "carbon window" spectral region (4.5 nm$<\lambda<$5 nm), where the carbon and carbon containing materials are extremely transparent. In this interval the absorption of radiation by most elements is ten-hundred times higher than by carbon. This fact defines a high sensitivity of imaging to local chemical composition and density and allows observe an internal microscopic structure of biological and medical objects. In the talk we demonstrate the soft X-ray images of artificial carbon fibers, laser fusion targets, various tissues of plants, animals and humans and other samples. The imaging was performed with a laboratory plasma X-ray source and Co/C multilayer optics. Obtained high-contrast images confirm a possibility to visualize the internal structure of thick (thickness 10-20 μm) carbon-based objects using transmission soft X-ray microscopy in "carbon window" region.

Further development of compact X-ray sources, high-throughput multilayer optics for carbonwindow microscopy and zone plates is believed to result in new laboratory instrumentation for study and control of various objects in biology, medicine, nanotechnology, microelectronics, organic chemistry, etc.

Multilayer X-ray optics for biomedical imaging

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Nonivasive imaging of small animal models has the potential to benefit every area of biomedical research for a diverse range of human conditions. Although techniques like computed tomography and magnetic resonance imaging provide spatial resolution to size scales of 10 microns, these imaging modalities are best used to visualize structure and anatomy. Studies of physiological function and metabolic processes, on the other hand, are best performed via radionuclide imaging methods like position emission tomography or single photon emission computed tomography. Currently, these techniques are limited to a spatial resolution of ~1 mm. In this talk, I will present our effort to develop hard X-ray multilayer optics capable of delivering sub-100 micron spatial resolution for small-animal imaging.

I will begin the talk by discussing the motivation behind our work and the important role that *in vivo,* small-animal imaging has in biomedical research. I will then describe our basic approach–employing reflective hard X-ray optics for direct imaging–and discuss the advantages it has over more traditional methods. I will conclude by presenting some recent results from prototype optics that clearly demonstrates the feasibility and promise of this technique.

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

Interplay between pattern formation and scale invariance in nanostructure production: mesoscopic descriptions.

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Recent results will be reviewed on the development of dynamical instabilities at nanometer scales in various surface and interface growth and erosion processes, leading to formation of nanometric sized patterns. We will also consider the occurrence of fluctuations in the morphology of such surfaces, as reflected in the scale invariance properties of the surface roughness. As the main physical examples, we will consider the production of nanostructures through sputtering by ion-bombardment at intermediate energies, and the dynamics of steps on epitaxial surfaces which are vicinal to a singular surface. We will thus illustrate the effectiveness and the limitations of Non-equilibrium Statistical Mechanics in the description of these systems.

In-situ X-Ray Scattering Study of Dynamic Scaling in Tungsten Film Growth and Ion Erosion

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The surface of a film growing or eroded under non-equilibrium conditions often evolves in accordance with the concept of dynamical scaling [1]. In this concept, several attributes, known as scaling exponents, serve as signature in space and time for growth or erosion processes that would, otherwise, appear as very complex. In principle, by comparing the experimental scaling exponents with the theoretical predictions one can establish the type of differential equation describing the film process. These considerations explain the greatly increasing interest for the dynamic scaling approach.

In this paper, we present results of in-situ real-time investigations on the roughness evolution during the growth and ion erosion of tungsten films using grazing incidence x-ray scattering, and we describe the novel experimental apparatus installed at the BM5 beamline of the ESRF [2]. We show that, by recording in-situ a single scattering diagram for a grazing angle of a probe beam exceeding the critical angle of total external reflection, it is possible to uniquely determine the two PSD-functions describing the micro-topography of the external surface and the film-substrate roughness conformity. Using this approach we have studied the temporal evolution of the roughness of sputter-deposited tungsten films and found that the roughness spectra obey a universal scaling form. In accordance with the scaling model the 1D PSD-function can be written in the following form: $PSD(p,h) \sim p^{-1-2\alpha} g\left(ph^{\beta/\alpha}\right)$. When plotting the PSD-function $PSD(p,h)p^{1+2\alpha}$ versus the spatial frequency $ph^{\beta/\alpha}$ (re-normalized quantities) for different film thickness h, all curves may be collapsed into a single master curve corresponding to the scaling function $g(u)$ providing the scaling exponents are properly chosen. In our problem this was achieved for $\alpha = 0.18 \pm 0.02$ and $\beta = 0.06 \pm 0.01$. In addition, by analyzing the temporal variation of the roughness conformity, we demonstrate that the replication factor decreases exponentially with increasing film thickness and spatial frequency. Hence, for a 25 nm thick film the vertical correlation disappears for spatial frequencies p greater than $3.6 \ \mu m^{-1}$.

Similar investigations were performed during subsequent argon ion etching of the grown W films. As above, we observed the data collapse of the PSD-functions when setting the scaling exponents to $\alpha = 0.35 \pm 0.05$ and $\beta = 0.2 \pm 0.03$. These values are consistent with the prediction of the KPZ equation [3], the simplest nonlinear equation used for describing film growth and erosion processes. Furthermore, we observed a rapid reduction of the roughness conformity with the erosion time. The data indicate that the vertical correlation disappears in the measurable range of the spatial frequencies ($p > 0.1\,\mu m^{-1}$) after removal of a tungsten layer only 5 nm thick.

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MAGNETRON SPUTTERING: MINIMIZING THE INTERFACE ROUGHNESS OF MULTILAYER MIRRORS BY COLLIMATION OF THE SPUTTERED MATERIAL

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In the optics-hutch of an arbitrary beam-line several multi-layer mirrors are present, either serving as band-pass filters or as a part of a focussing element. In order not to loose too much intensity, it is of great importance that the reflectivity of each mirror is as high as possible. Important parameters in relation to this are of course the multi-layer interface roughness and the length of the mirror. Assume that the minimum wavelength of the beam-line is 0.4 Å, the beam-height is 1 mm and the multi-layer period is 50 Å. The glancing angle is then as small as 4 mrad, so the resulting footprint on the mirror is 250 mm long. Due to the small glancing angles, in the world of x-ray optics there is a strong demand for long (say half a meter) high-reflectivity multi-layer mirrors. Dependent on the bandwidth of the incident beam, the variation in d-spacing along the length of the mirror should be kept below a certain limit. Also it may be useful to minimize the width of the Bragg peak. Here we will report on how we have obtained a rms roughness below 3 Å and a d-spacing variation of $\pm 0.5\%$ over a 250 mm mirror. The results are based upon x-ray reflectivity measurements of 10 bilayer SiC/WC multi-layers. As substrates we have used either Si wafers with a rms roughness of 2.5 Å or float-glass. The multi-layer coating is done at the sputtering facility at the Danish National Space Center. This set-up is described in detail in [1].

Experience tells us that in the sputtering chamber, the optimal pressure of Ar during the coating is 3 mTorr (0.4 Pa). To some extent, there will be some scattering of the sputtered material on the Ar ions. By coating with different degrees of collimation of the sputtered material, we have investigated how this scattering affects the roughness of the obtained multi-layer mirror. The collimation is obtained by placing the substrate between a pair of separator-plates as sketched in the figure to the left. The sputtered material is symbolized by arrows. Grey arrows indicate material which do not reach the substrate due to the collimation. We have shown that

- the roughness is decreased by the collimation
- the thickness of the WC layer is not affected by the collimation.
- the thickness of the SiC layer is decreased by the collimation.

The view-graph in the middle shows $\Gamma_{\mathrm{SiC}} = d_{\mathrm{SiC}}/d$ (circles) and the rms interface roughness σ (squares) as function of the opening angle $\alpha = \arctan(D/(2S))$ of the collimator towards the target. An opening angle of 90° corresponds to no collimation at all. These observations lead us to the conclusion that an important contribution to the roughness is coming from the energy-loss of SiC by the scattering on Ar. These results are obtained by coating on float-glass with a minimum roughness of 3 Å, so we cannot expect to obtain an interface roughness smaller than that. Other experiments show that further collimation will not decrease the roughness, but only lead to an increase of the coating time. When using Si wafers as substrate and collimating with a honeycomb-mesh, we obtain a roughness below 3 Å and a homogeneity in the d-spacing within $\pm$ 0.5% over a 250 mm long mirror .

We have shown that due to wearing of the target, the coating rate decreases linearly with the total elapsed coating time, that is the 'age' of the target, *when the power supplied to the cathode is kept constant.* To keep the d-spacing constant through the whole stack, it is thus necessary continuously to decrease the speed of the substrate relative to the cathodes (anti-grade), so that the topmost layer is obtained with a speed which is smaller than the initial speed. The view-graph to the right shows the Full Width at Half Maximum of the 1st and 2nd order Bragg peak as function of anti-grading. These results are from 100 bi-layers of W/Si with $d \approx 25$ Å. The error-bars are of the same size as the data-point markers. This example confirms that the width of the Bragg peaks can be minimized by anti-grading, in this case by approximately 1%.

The aim is to make use of these results in the production of a focussing device to the Compact Light Source (see www.lynceantech.com).

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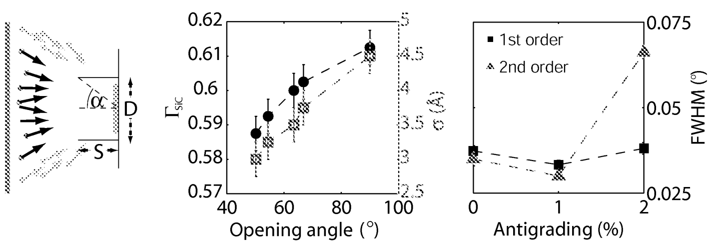

Roughness propagation in short-period Cr/Sc and Cr/Ti multilayers

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In spite of the advancements in soft X-ray multilayer mirror performance the achievable normal-incidence reflectivities are still far below theoretical values. An understanding of layer morphology, interface definition, as well as vertical roughness propagation is important to improve multilayer mirror performance further. In this work structural differences in multilayer growth of Cr-based multilayers using Sc and Ti as counter-materials have been investigated.

Multilayers were grown by magnetron sputter deposition in an ambient temperature and the consequences of low ion-energy (2 eV-50 eV), high ion-flux (Φ_{Cr}=7 , Φ_{Sc}=23, Φ_{Ti}=3.2) have been studied for bilayer thicknesses <2 nm. An assistance of high flux sputtering gas ions during growth, in combination with a two stage ion-energy modulation of each individual layer resulted in extremely flat interfaces with significantly reduced intermixing and average interface widths on the order of 0.3 nm.

In Fig.1 the measured and calculated soft X-ray reflectivities are shown as a function of increasing number of bilayers for Cr/Sc and Cr/Ti. The reasons for substantial differences in state-of-the-art measured near-normal incidence reflectivities ($R_{Cr/Sc}$=20.3% and $R_{Cr/Ti}$=2.1%) and theoretical predictions at the Sc (λ=3.12 nm) and Ti (λ=2.74 nm) absorption edges were explored by specular and diffuse hard and soft X-ray reflectivity (XRR) measurements and transmission electron microscopy (TEM).

The nano-structural local roughness evolution at interfaces and in the whole multilayer stack was studied by TEM. The roughness propagation with increasing number of bilayers was found to predominantly be an accumulating local atomic distortion (jaggedness) for Cr/Sc, while low spatial frequency roughness (waviness) was observed to accumulate for the Cr/Ti multilayer system.

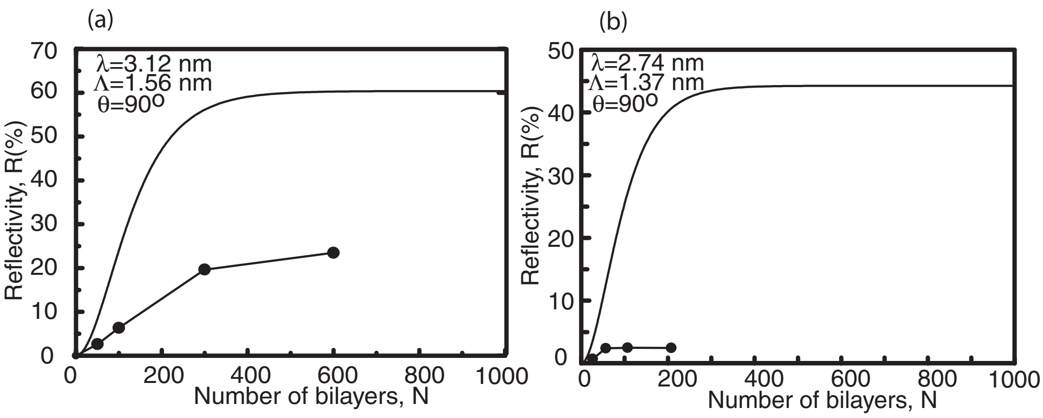

Figure 1: Absolute reflectivities measured for (a) Cr/Sc at the Sc-*2p* absorption edge for multilayers containing 50, 100, 300 and 600 bilayers, (b) Cr/Ti at Ti-*2P* absorption edge for multilayers containing 20, 50, 100 and 150 bilayers. Theoretical reflectivity profiles are plotted for comparison.

Development of multilayer mirrors for the 20–50 nm wavelength region at LCFIO

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During last years, the X-UV Optic team of Laboratoire Charles Fabry de l'Institut d'Optique (LCFIO) has focused its research on the development of multilayer mirrors for the 20–50 nm wavelength region. This region is of particular importance for EUV astrophysics, high harmonic generation (HHG) sources, x-ray laser sources and others applications.

In the 20-40 nm range, we have shown previously the interest of three component periodic multilayers. Simulations show that multilayers made of B4C, Mo and Si materials present higher reflectivity than 2 component multilayers (B4C/Si and Mo/Si). B_4C/Mo/Si structures present a theoretical reflectance of 42 % at =32 nm which represents a great improvement as compared with B_4C/Si or Mo/Si multilayers in this region [1]. We will present here the last results that we have obtained by combining several 3 component multilayers in non periodical structures in order to design new mirrors as broadband mirrors or double band mirrors. Both design optimization and experimental results will be presented and discussed. A comparison between simulation and measurements of the reflectivity spectrum of different kind of mirrors (single multilayer or broadband mirror) will be provided.

In the 40-50 nm range, we have designed and deposited Sc/Si multilayers with high reflectivity (up to 46%), good temporal stability (no decrease after 500 days of aging). Thermal stability of Sc/Si multilayers with three kinds of barrier layers (SiN, ScN and B4C) has been studied as a function of the barrier layer thickness. The optimization of the barrier thickness results from a compromise between the as deposited reflectivity value (which decreases when the barrier thickness increases) and the loss of reflectivity after thermal treatment (which increases when the barrier thickness decreases). A comparative study of experimental and theoretical reflectivity calculated by using recently published Sc optical constant values will be presented.

In conclusion, examples of application of such new kinds of multilayers to EUV astrophysics and to optics for HHG sources will be provided. Narrowband multilayer mirrors have been designed and deposited for the selection of high harmonics in the range 30 nm – 50 nm (harmonic order from 17 to 25). Experimental reflectivity higher than 20% has been obtained with rejection ratio of the neighboring harmonics higher than 10.

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High-Reflectance and Narrow-Bandpass Multilayers for the 60 nm Wavelength Region Utilizing the Rare Earth Elements Tb, Gd, and Nd and with B_4C Barrier Layers

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Multilayers utilizing a rare earth element Tb, Gd, or Nd in combination with Si were fabricated and characterized using synchrotron radiation. The multilayer parameters were designed for high normal-incidence reflectance at wavelengths near 60 nm using the optical constants experimentally determined from the transmittances of thin films on silicon photodiode substrates. The performance of multilayers with and without B_4C barrier layers were compared. The results indicate the potential for designing and fabricating multilayer-mirror telescopes for narrow-bandpass imaging of the intense O V 63 nm solar emission and other emissions in the 55-70 nm wavelength range.

Multilayer reflectivity and stress responses upon isothermal treatment

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Multilayer structures are being proposed for x-ray optics applications such as monochromators or focusing optics at third generation synchrotron radiation sources. When placed as the first optical element they may be exposed to high thermal load. Hence, thermal stability requirements of the optical elements are stringent. Thermal behaviour of multilayers depends sensitively on the period thickness of the multilayer system, its thermal history, and the preparation technique. To investigate the influence of a thermal action on the reflectivity response of multilayers produced by Distributed Electron Cyclotron Resonance sputtering at ESRF is a real challenge: controlled thermal treatment of multilayer optics before their installation on synchrotron beam lines to avoid any further alterations during their use as optical elements. An important issue is to reduce stress introduced by the coating on substrates. The evolution of stress in multilayer test coatings deposited on wafers was worked out from measurements done by optical metrology before and after coating and annealing.

We will present our experimental approach: multilayer choice, isothermal sequence, reflectivity and stress measurements. We will also discuss compromises made to keep both reflectivity and stress optimized versus thermal treatment. Future studies will have to deal with the impact of radiation on multilayer optics and its distinction from annealing effects.

Keywords: x-ray optics, multilayers, reflectivity, stress, isothermal annealing

Progress in short period multilayer coatings for water window applications

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Multilayer coatings for normal incidence optics designed for the water window region (2.3 nm < λ < 4.4 nm) are particularly challenging since a layer thickness below 1 nm is required. At normal incidence the roughness induced scattering increases as $(\sigma/d)^2$ making it difficult to achieve high reflectivity as the period, d, is reduced. Recently, Cr/Sc multilayers have been fabricated[1,2] with normal incidence reflectivity in the vicinity of 20% for wavelengths near the Sc edge at 3.11 nm. Motivated by this success we have investigated the use of diffusion barriers for short period multilayers. Such diffusion barriers have been successfully applied to Mo/Si multilayers in the EUV.[3,4]

The multilayers were deposited by conventional magnetron sputtering. Using an additional B_4C layer a reflectivity of 32% was achieved at 3.11 nm at an angle of 10 deg from normal. The Cr/Ti and Cr/V multilayer systems have also been investigated. In the case of Cr/Ti a near normal incidence reflectivity of 17% was obtained near the Ti L edge at 2.73 nm. For Cr/V a near normal incidence reflectivity of 9% was obtained near the V L edge at 2.42 nm. These results are very encouraging for the possibility of more widespread applications of normal incidence optics in the water window range.

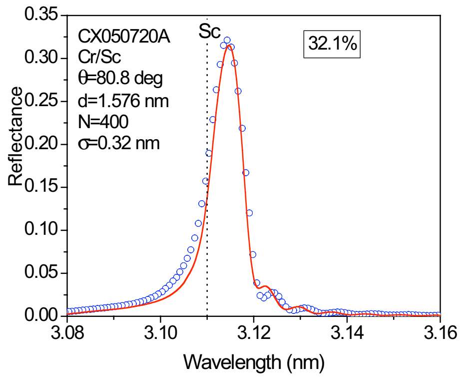

Fig. 1. The reflectivity measured for a Cr/Sc multilayer with B_4C barrier layers at an angle of 9.2 degrees from normal incidence.

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Investigation of Ru-based multilayers for synchrotron applications

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For synchrotron applications in the energy range of 10-22 keV Ruthenium based multilayers are the best choice. Calculations of the ideal system show that Ru/B4C and Ru/C should be the best suited layer combinations. The theoretical reflectivity for a Ru/C multilayer with dspacing of 4 nm is about 76% (roughness 0.3 nm, bulk density) at CuKα. We achieved experimental reflectivities of 70% +/- 3% at Cu-Kα. An extrapolation to the energy of interest for synchrotron applications gives reflectivities of 79% at 10keV and of 92% at 22keV. To investigate the difference between calculation and experiment we performed transmission electron microscopy of cross-sectional specimens from Ru/C multilayer systems with layer thicknesses in the nanometer range. It was found that the Ru/C layers consisting of 30 or 100 bilayers, respectively, are deposited regularly with a uniform growth and thickness on the substrate. By applying a geometric phase method which has been originally developed for measuring displacement fields from high-resolution TEM images, the structural perfection of multilayers, especially their local layer periods and local layer orientations, can be analyzed with high sensitivity [1].

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Multilayers in Laue geometry

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The development of next generation x-ray sources (such as x-ray free electron lasers) will enable new, exciting applications in biophysics, material sciences and basic science. However, to efficiently utilize these new sources more work needs to be done in the development of x-ray optics. High resolution diffractive optics requires high-aspect-ratio structures, which challenges the limits of lithographic techniques. An alternative approach is to make a cross section of a multilayer film, as in "sputter-slice" zone plates. The challenge is to deposit thick (many microns) multilayers with high precision and maintain the structure during sectioning. The fabrication of thick multilayers demands extreme control of layer thickness, interface roughness and intrinsic stress. We will present the data from thick multilayers in Laue (transmission) geometry that have been studied in the soft and hard x-ray region and discuss their properties.

This work was performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48 and by the U.S Department of Energy, Basic Energy Sciences under contract W-31-109-ENG-38.

Sub-ps Laser Patterning of Multilayer Structures for X-Ray Gratings and Sensors

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Laser processing of thin films has become a field of growing importance with many applications including manufacture of micromechanical devices and fabrication of novel, high performance electronic circuits and optoelectronic devices. Laser processing depends on the optical properties of the material and on the wavelength and pulse duration of the incident light. The energy of laser pulses is absorbed mainly within the optical penetration depth and is dissipated within the thermal diffusion length. The thermal diffusion length is of the order of 1000 nm and 10 nm for a ns and ps laser pulses, respectively, which means a substantial difference. Comparative studies verified that sub-ps laser processing may be more suitable for high resolution applications.

The micropatterning of W/Si, Si/W, Mo/Si, Si/Mo, Ag/Co and Co/Ag multilayer structures for applications in X-ray optics and magnetic field giant magnetoresistance sensors is described. The multilayers were prepared by UHV e-beam evaporation onto silicon, oxidized silicon or glass substrates. A micromachining system was operating with 0.5 ps laser pulses. The hybrid distributed-feedback dye-laser/excimer laser delivering 10 mJ/pulse at 248 nm wavelength and at 4 Hz repetition rate was used. Periodic multilayers with double layer thickness (period) up to 10 nm and with 3 - 10 periods were patterned, laser fluence varying between 60 and 710 $mJcm^{-2}$. The multilayers were locally ablated up to the substrate or deeper using 1 - 5 pulses directed to the same site forming thus grooves with sub-micrometer width. The patterned area up to $900 \times 900\ \mu m^2$ required the patterning time of $\approx$2 hrs. Atomic force microscopy, scanning electron microscopy, X-ray reflectivity, X-ray diffraction and resistometry were used to characterize the multilayers and patterned structures. The surface roughness of stripes and grooves of the patterned structures increased with the depth of ablation which is caused first of all by debris. High needles were occassionally observed` in the grooves of Ag/Co and Co/Ag structures. This effect is attributed to the mutual immiscibility of the respective components and is analyzed further. The main advantage of the patternig of multilayers with nm thick sublayers by sub-ps pulses is the preservation of the multilayer structure which is not intermixed during the ablation. The X-ray ω – scans around the 1st Bragg maximum show symmetric satellites up to the 2nd or 3rd order, giving the evidence that the multilayer structure inside the stripes is preserved as expected for a processing in the sub-ps region with minimized thermal effects. The energy for ablation of one atom calculated from the fluences, number of pulses and dimensions of the grooves was found to be between 25 and 45 eV, being averaged for the two respective components. This result means that we work close to the low energy limit where the ablation energy is used for bond breaking only and the thermal dissipation is low. Nearly rectangular (partly trapezoidal) grooves were formed in the multilayers by the sub-ps laser patterning. For comparison, the patterning was performed also by standard 30 ns excimer KrF pulses. Here, *v* - shaped grooves were obtained which was attributed to a more isotropic ablation due to the higher thermal diffusion length. Approximately 40 times higher fluences than with sub-ps laser were required for the same depth of ablation. In conclusion, the sub-ps laser patterning proved to be a powerful tool for fabrication of sub-micrometer structures from metallic multilayers with several nm layer thicknesses based on a simple one-step process.

Compact X-Ray Microscopes with Multilayer Mirrors

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Abstract

X-ray microscopy in the water-window region (λ = 2.3-4.4 nm) is an attractive technique for high-resolution imaging. In this wavelength region state-of-the-art optics has demonstrated sub-30 nm resolution and the sample preparation techniques are maturing. Unfortunately present operational x-ray microscopes are based on synchrotron radiation sources, which limit their accessibility. Many investigators would benefit from having the x-ray microscope as a tool among other tools in their own laboratory. For this purpose we demonstrated the first compact x-ray microscope with sub-visible resolution.[1] In this presentation we will describe this microscope and its recently developed follow-up generation. The microscope is based on a 100 Hz methanol-liquid-jet λ=3.37 nm laser-plasma x-ray source[2], multilayer condenser optics, diffractive zone plate optics and CCD detection.

The condenser is a critical component in the microscope. Here normal-incidence spherical multilayer mirrors offer interesting advantages compared to diffractive optics. The numerical aperture (NA) can easily be matched to the NA of the zone plate optics, which is important for resolution. The collection efficiency can be high, resulting in reasonable exposure times. The limited band width offers spectral selectivity of the source spectrum, thereby avoiding blurring in the subsequent highly chromatic micro-zone-plate imaging. Alignment in the microscope is easy. However, the demands are severe. Interdiffusion and roughness must be minimized for high reflectivity at these short d-spacings. The uniformity of the d-spacing must be very high over the full area of the mirror. In addition, these microscopes are operated with narrow-line-width laser-plasma sources, where the emission wavelength is determined by an atomic transition. Thus, the d-spacing must not only be uniform but also match the pre-determined emission line over the full mirror area.

Several multilayer laboratories have fabricated mirrors for our compact x-ray microscopes. The first W/B_4C condensers by Y. Platonov exhibited 0.2-0.5% average reflectivity over the 58 mm diam.[3] J. Birch's group improved processing resulting in >5% Cr/Sc reflectivity at λ=3.37 nm over small areas. Recently S. Yulin manufactured 58 mm diam Cr/Sc condensers, which appear to have 2.5-3% average reflectivity at λ=3.37 nm, thereby improving exposure times >10× compared to previous systems. In this paper we will discuss x-ray microscopy based on multilayer condensers and compare with other condenser concepts.

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Abstract Cancelled

Free-standing multilayer Cu/Zr foils for adaptive optics: Making lightweight mirrors by replication

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Adaptive Optics (AO) surfaces have been proposed as a way to field optics simultaneously achieving high optical figure accuracy, ultrasmooth optical finish (σ < 0.5nm rms), and light weight (< 2kg/m^2) in visible-wavelength segmented-mirror telescopes [1]. Such AO telescopes comprise a deformable face sheet acting as the optical surface, an array of actuators controlling the figure of the face sheet, and a lightweight superstructure. Face sheet materials are most commonly silicon or glass, but these suffer from low toughness. Metal multilayer or "nanolaminate" foils have been developed at LLNL that are a significant advance in face sheet material.

Nanolaminate foils of Cu and Zr with total thickness 2.5-5µm have been fabricated by magnetron sputtering at pressures of a few mTorr. The individual layers are 4-40nm thick with ~100-200 layers total. An initial parting layer is applied to allow separation of the foil from the substrate. Initial and final layers of Au are applied for optical reflectivity on the replicated surface and to allow gold-bump bonding to actuator structures on the back surface. Actuation is by parallel-plate electrostatic MEMS actuators mass fabricated by microlithography methods.

Primary technical challenges include fabrication of the nanolaminate foil with sufficient flatness (R_c> 40cm) so the foil does not require force from the actuators to pull it flat. This requires management of stress gradients that occur through the thickness of the foil during growth. Substrates were preheated to compensate differential thermal stresses during growth, though additional stress gradients appear to contribute to curvature also. Foils with R_c> 50cm for foils as thin as 2.5µm were achieved by this method. A mechanical model of the residual stresses and final curvature of the foils will be presented. Replication of roughness from the substrate to the replicated surface will also be presented, with an assessment of the role of system geometry in local control of film stress.

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keywords: adaptive optics, replicated optics, free-standing, thin films, curvature, stress, thermal stress

Reference

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Poster Session 1
Monday March 13th, 2006

Abstracts

Wideband Multilayer mirrors for EUV optical systems

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Normal incidence multilayer mirrors opened up new opportunities to produce high resolution imaging optics for EUV and soft x-ray spectral regions. However, the interference nature of reflection, resulting in a narrow spectral and angular band pass of a multilayer mirror sometimes limits the ultimate possibilities of multilayer optics. In this work, optical properties of depth-graded multilayer mirrors of different composition providing constant reflectivity at 13.5 nm wavelength in a wide angular range have been considered. It is theoretically shown that a reflectivity up to about 60% can be achieved in the [0, 18^{o}] range of the incidence angle. The effect of different physical and technological factors on the reflectivity are discussed. The first experimental results are presented.

[Cu/SiC]/[WC/SiC]/Si for hard x-ray telescope designs

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The materials chaise for depth graded multilayer designs for hard x-ray telescopes (above 10 keV) have until now been focusing on W/Si, W/SiC, Pt/C, and Pt/SiC. These material combinations have good stability over time and low interface roughness. However both W and Pt have absorption edges in the energy range from 70 keV to 80 keV. Looking at the optical constants for Cu it would be good alternative high-Z candidates since the k-absorption edges for Cu is below 10 keV. Unfortunately Cu/Si coatings are unstable over time, Windt et al, and not much work has therefore been done with Cu.

We will present data for 10 bi-layer coatings of Cu/SiC that are stable over a period of 2 years, see figure 1. These coatings have d-spacings between 45 nm and 178 nm and a roughness of 0.4 nm to 0.7 nm. With the relative high roughness of the coatings it will not be possible to make very thin coatings with this material combination. The thin coatings are needed to make x-ray telescopes working at higher energise.

As we showed here at PXRMS 2 years ago, we have made WC/SiC coatings with roughness in the range between 0.17 nm and 0.25 nm. As a result of this low roughness we have since made WC/SiC coatings with d-spacing down to 0.8 nm.

By combining the very thin WC/SiC coatings in the bottom of a depth grated multilayer with the Cu/SiC coatings in the top in the same stack this allows for novel telescope designs operating up to and above 100 keV without the absorption edge structure.

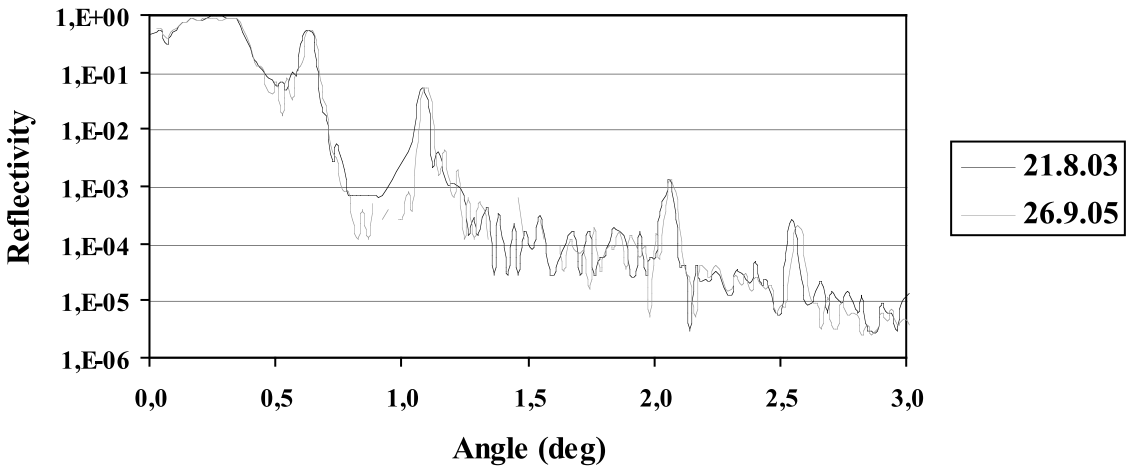

Figure 1: A 10 bi-layer Cu/SiC coatings with d-spacing at 8.7 nm and a roughness of 0.45 nm, measured with more than 2 years apart.

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ESRF developments for 40 nm focusing with dynamically-bent graded multilayers: Multilayer characteristics and associated metrology

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A one-dimensional focusing system was developed to achieve focal lines below 100 nm. The focusing setup is based on half bender and a pre-shaped substrate covered with a graded multilayer A focal spot size below 50 nm has been obtained in vertical reflection at a distance of 8cm from the centre of the mirror using synchrotron radiation from ESRF beamline ID19 undulator line at 24 keV . Focusing multilayer optics generally require a lateral thickness gradient to account for the variation of the incident angle given by the focusing geometry. The bending technology, the multilayer coating, and the detection setup are ESRF in-house developments.

The deposited multilayers characteristics will be given: the design of layer structure, the growth aspects and the lateral gradient optimized in view of the technical limitations of our deposition process. This graded multilayer structure fulfils the local Bragg condition at any point along the optics. The micro-roughness and the mirror figure errors before and after the deposition and after elliptical figure optimization with the mechanical bender were studied by optical metrology. It will be shown that both basic physical and technological constraints limit the measured line width .

Keywords: multilayers, focusing hard x-rays, metrology , synchrotron radiation

Evolution of the morphology of a tungsten film during growth, erosion, and oxidation

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In the understanding of thin film growth, erosion, or oxidation, the evolution with depth of both the roughness and the dielectric constant are of utmost interest. Until now, these problems have been independently studied using simplified assumptions. In this paper, we propose to solve simultaneously the problems of the quantitative analysis of the roughness and of the extraction of the depth-distribution of the dielectric constant. Indeed, roughness influences the reflectivity curve, while the depth-graded dielectric constant, in its turn, results in a change of the wave field distribution inside the sample, thus modifying the scattering pattern.

An experimental facility located at the ESRF BM5 beamline [1] allows to perform real-time in-situ x-ray scattering measurements during sputter growth and etching [2]. A 5-nm thick tungsten film was deposited, and the following measurements were performed: scattering diagrams at different grazing angles of the probe beam at fixed energy (E=17.5 keV), reflectivity versus grazing angle, and reflectivity versus deposition time at fixed grazing angle ($\theta=0.5^{o}$).

The data analysis started with the extraction of the three PSD-functions characterizing the film roughness, including the PSD-function of the substrate-film interface, under the assumption of the tungsten density to be constant in the depth of the film. When estimating the tungsten concentration versus depth, the effect of roughness was neglected. Then, we performed an iterative procedure where the interfacial roughness was taken into account for deducing the depth-distribution of the tungsten density and vice versa. After several iterations the procedure was shown to converge, resulting in the refined description of the film morphology both in depth (density profile) and in the lateral direction (roughness). Similar experiments and data processing were performed both after ion erosion of the deposited film over a depth of about 1 nm and after oxidation of the same film in air. The comparison of the results obtained allows us to explore the way roughness develops during erosion and oxidation and to evaluate the decrease of roughness conformity between film and substrate as well as the change of tungsten density with depth.

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Fabrication of wideband multilayer mirrors at EUV wavelength region

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EUV multilayer mirrors are key components for high resolution imaging in a microscope we are now developing. A multilayer is composed of alternate thin layers of two suitable materials for constructive interference. For achieving high throughput by multilayer mirrors of narrow bandwidth $\lambda/\Delta\lambda$ of several tens to hundreds composing EUV imaging optics, reflection peak wavelength matching is indispensable. Accurate thickness control and/or high stability of deposition rate are necessary to realize exact wavelength matching. To overcome these difficulties by widening reflection bandwidth, we have developed a design method using optimization algorithms and fabricated Mo/Si multilayer mirrors with wideband reflectance profile.

By using design software we developed, thicknesses in a Mo/Si multilayer were optimized to minimize the deviation from desired s-reflectance of 36 % at wavelength region from 12.6 nm to 14.4 nm. As for the initial structure, a 40 period Mo/Si multilayer was used at angle of incidence of 30 deg. Their thicknesses were set to 3.12 nm for Mo and 4.91 nm for Si, respectively. Aperiodic thickness distribution obtained is shown in Fig. 1. The thicknesses of the lower periods are randomly varied, however the upper periods show a depth-graded-like distribution. The wideband multilayer on a Si substrate was fabricated by our ion beam sputtering (IBS) system. For fabrication of aperiodic thickness distribution, computer programmed target control system was installed in the IBS system.

EUV reflectance of wideband Mo/Si multilayer mirror was measured at BL-12A, Photon Factory, KEK with a reflectometer. As a reference, EUV reflectance of a periodic Mo/Si multilayer mirror was also measured by a laboratory reflectometer with a laser produced plasma. As shown in Fig. 2, s-reflectance more than 15 % was achieved at wavelength from 12.6 nm to 14.4 nm. Comparing with the reference mirror, the wideband multilayer with the spectral bandwidth more than 2.5 times was successfully fabricated.

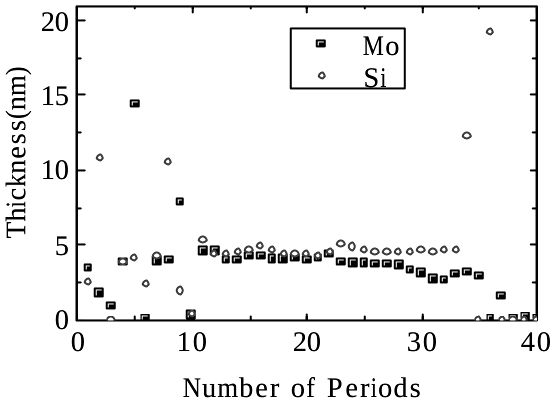

Fig. 1 Designed layer thickness distribution for wideband Mo/Si multilayer mirror.

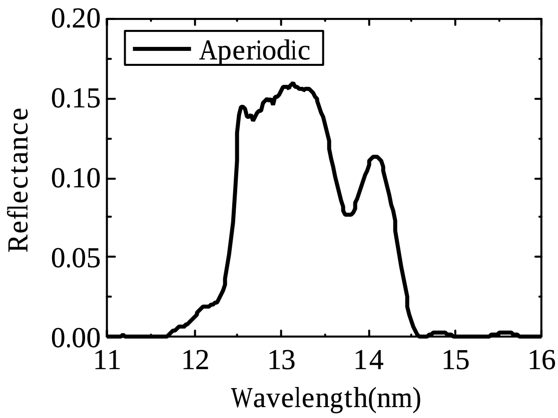

Fig. 2 Reflectance of wideband Mo/Si multilayers composed of 40 periods on Si substrate.

Borrmann Effect in EUV Multilayer Optics

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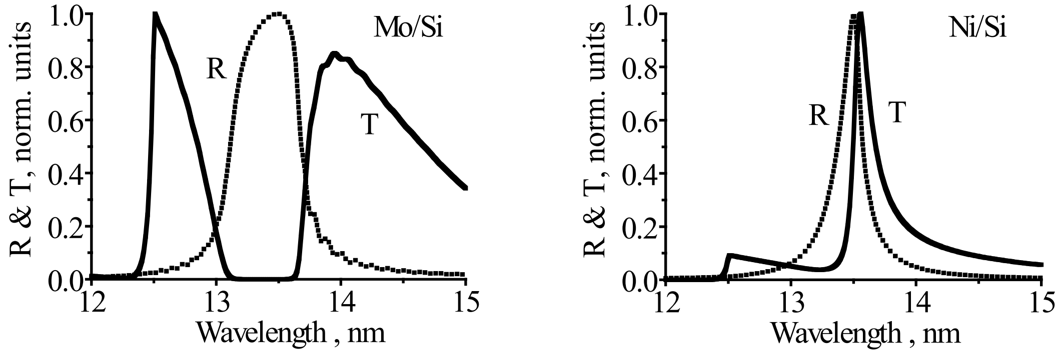
In the figure the reflectance and the transmittance of two free-standing periodic multilayer structures, Mo/Si and Ni/Si, operating at normal incidence are presented. The left graph demonstrates the typical case for EUV or X-ray multilayer optics: the minimum transmittance is achieved inside the Bragg peak, because interference effect results in an essential decrease of a radiation penetration depth into a multilayer structure. Outside the Bragg peak the transmittance of a Mo/Si mirror is almost the same as an uniform film with the mean value of the absorption coefficient and of the same thickness as the multilayer structure.

In contrary, both the transmittance and the reflectance of Ni/Si multilayer filter achieve the maximum value in the same narrow spectral interval (right graph). Outside the Bragg peak the transmittance of Ni/Si filter corresponds to a uniform film as well. However, inside the Bragg peak, we observe anomalous high transmittance, which is 25 times more than for a uniform film. This phenomenon is an analogous of the Borrmann effect observed under transmission of hard x-rays through crystal.



In our presentation we analyze the physical reasons of the Borrmann effect appearance, which are connected with the specific wave field distribution inside a multilayer mirror, and demonstrate that the effect appears only in case of a large difference in absorption of materials composing the structure. The choice of materials, thickness ratio optimization, possibilities of decreasing of transmittance width, the effect of interlayers as well as possible applications of the effect are discussed.

Effects of concurrent low-energy, high-flux ion irradiation during magnetron sputter deposition of Mo/Si multilayers

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The effects of low-energy, high-flux Ar ion assistance during sputter deposition of Mo/Si multilayers have been investigated.

Mo/Si multilayers with nominal bi-layer periods of $\Lambda \approx 7$ nm were deposited in a dual dc magnetron sputtering system with high Ar-ion-to-metal flux ratios of 2.5 and 9.5 during growth of Mo and Si, respectively. The ion energies were set at very low values (1-61 eV) by negatively biasing the substrate.
The ion irradiation influence on interface roughness, and intermixing, $MoSi_2$ preciptation, and Mo amorphous-to-crystalline transition were investigated by hard X-ray specular and diffuse reflectivity, high-angle X-ray diffraction, as well as high resolution transmission electron microscopy.

With continuous ion assistance with about 24-26 eV Ar-ions, a best trade-off between interfacial roughness and ion induced intermixing ws obtained. Anomalous re-sputtering during Si growth, due to sputter yield amplification, by Ar ions penetrating the growing Si-layer and back-reflecting from the topmost Mo-layer, was observed to an increasing extent when the ion assisting energy was increased from 1 to 61 eV. At the highest energy, the re-sputtering rate equaled the deposition rate, leaving no net Si deposition. Clear non-uniformities in the bi-layer periodicity were observed for 50 bi-layer multilayers grown with continuous ion assistance when compared to 20 bi-layer multilayers deposited using the same conditions, indicating the occurrence of a thickness-driven phase change during growth.

To further improve the Mo/Si interfaces, the ion assistance energy was modulated within each layer where the initial few atomic layers of each layer were deposited with no ion assistance to minimize intermixing, reduce sputter yield amplification, and limit ion induced silicide formation. The remaining parts of each layer were subsequently grown with higher assisting energies to densify the layers and produce smooth top surfaces for the next layer to form upon.

The best overall quality of the Mo/Si multilayers was obtained using initial layers with thicknesses of 0.9 and 0.3 nm for Si and Mo, respectively, where an Ar-ion energy of 1 eV was used, and then irradiating with 59.5 eV and 26 eV ions during deposition of the remaining Si and Mo parts. This deposition scheme also eliminated the bi-layer period non-uniformity observed with continuous ion assistance so that multilayers containing up to 50 bilayer periods could be deposited without any observed irregularities in the hard X-ray reflectivity curves.

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Off-plane grazing incidence blazed grating with radial groove geometry as an efficient spectral purity filter for EUV lithography

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Separation of the broad-band emission spectrum from laser- or discharge-produced plasma sources of high power extreme ultraviolet (EUV) radiation requires a specialized spectral filter. Harnessing a reflective blazed diffraction grating which works in the off-plane grazing-incidence mount is apparently the most efficient and rather simple way to separate the 2% wavelength band in the vicinity of 13.5 nm. Relative efficiencies in the range from 0.95 to 1.0 and reflectances from 0.79 to 0.95 for incidence angles between 72° and 84° can be achieved for the non-polarized light incident from a EUV collector on such a grating which is higher than for the in-plane configuration (Fig. 1).[1] The calculated absolute integral efficiency of a single grating which works in a wide convergent beam decreases significantly from maximum values, however it can be compensated by grating segmentation. A plane high frequency grating which has a radial groove geometry is used as a model to select the desired spectral range and for providing record efficiency and focusing stigmatic image at high dispersion of adjacent orders. Among other advantages, the proposed solution is very useful for implementation based on novel technologies for shaping, patterning, and replicating sawtooth gratings, which can include anisotropic etching of specially-cut silicon wafers to pattern automatically smooth groove facets (rms roughness <0.2 nm), scanning-beam interference lithography to fabricate large-area (up to 300 mm in diameter) low-pitch gratings (>100 nm) with varied line space, and nanoimprint lithography to replicate gratings with good reproducibility and at a low cost. The author does not claim that only this technique works; rather, it is preferable for manufacturing such gratings. A silicon grating of this type can be actively cooled in a variety of ways in order to absorb the radiation-induced power. Efficiency measurements for a grazing-incidence diffraction grating, produced by the technology mentioned and planned for the Constellation-X Reflection Grating Spectrometer, were recently performed using the polarized synchrotron radiation.[2] The off-plane TE and TM efficiencies for a 200 nm-pitch test grating with 7.5° nominal blaze angle patterned on a 100 mm-diameter silicon wafer were measured and compared to the efficiencies calculated using the PCGrate®-SX™ code based on the rigorous integral method. The calculated and measured efficiencies are in quantitative agreement when using an average groove profile derived from atomic force microscopy (AFM) measurements. An extremely high –1st order absolute efficiency of ~0.45 is observed at ~2.5 nm wavelength of the TE-polarized radiation incident on a gold-coated grating. The same real (e.g. AFM-measured) groove profile and sawtooth profiles with different angles and pitches were used in the efficiency modeling for purposes of this report. More than 0.77 of the relative efficiency and ~0.72 of the absolute efficiency is predicted in the –1st order of a Mo-coated test grating with the AFM-measured groove profile accounting 0.5 nm rms roughness at the wavelength 13.5 nm and non-polarized light incident within a definite angle range (Fig. 2).

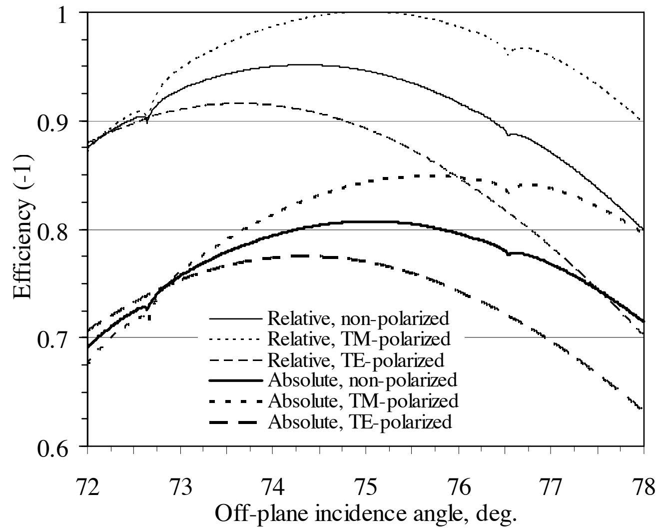

Fig. 1. The –1st order relative and absolute efficiencies of a Mo 5000 groove/mm sawtooth grating with 7.5° blaze angle calculated for 13.5-nm-wavelength radiation incident at 7.5° polar angle versus azimuth incidence angle of the off-plane mounting.

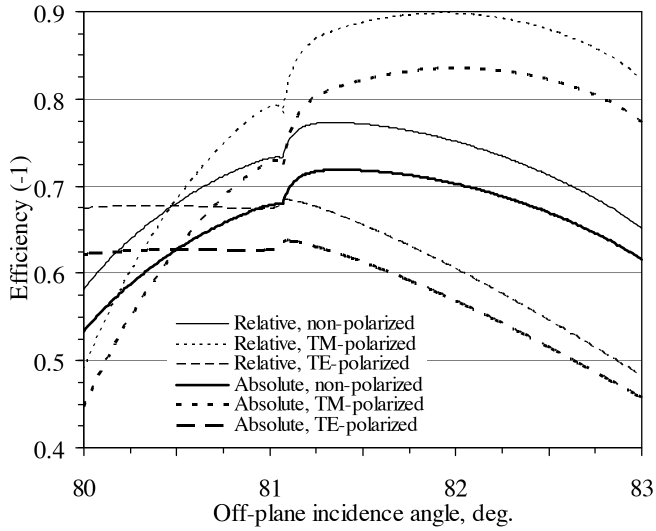

Fig. 2. The –1st order relative and absolute efficiencies of a Mo 5000 groove/mm grating with AFM-measured groove profile and rms roughness of 0.5 nm calculated for 13.5-nm-wavelength radiation incident at 7.5° polar angle versus off-plane incidence azimuth angle.

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Multilayer Mirrors for Use in an Energy Range of 1-8 keV

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The absorption edges as well as the characteristic emission lines of many elements are located in the energy range of 1-8 keV, in which the materials interact strongly with x-rays by photo absorption, photoelectron emission, and fluorescence. The x-rays in this energy range have been applied comprehensively to elemental analysis. In the energy region of 1-8 keV, the reflectivity of bulk materials is very low except at grazing incidence angles. Unfortunately, small grazing incidence angles invite large aberrations in the optical system and small acceptance of the flux from x-ray source simultaneously. The development of multilayer mirrors, allows one to obtain high reflectivity mirrors at large incidence angles. The multilayer coating technique may also be used to extend the applicable energy range of diffraction gratings to energies above 1 keV.

Considering the above issues, we have initiated a program to develop the multilayer mirrors for use in the energy range of 1-8 keV. As a result of theoretical investigation (Fig. 1), we have found that Co/Si multilayer shows relatively high reflectivity in the energy range of 3-7 keV. At energies above the K-absorption edge of cobalt (7.7 keV), the reflectivity of Co/Si multilayer mirror is reduced.

We have fabricated a Co/Si multilayer mirror using an ion beam sputtering method, and evaluated the layer structure of fabricated multilayer mirror with x-ray diffraction.

In this presentation, we will discuss the details of the fabrication and evaluation of multilayer mirror, and give some results of soft x-ray reflectivity measurements carried out using a synchrotron radiation beam lines at the Advanced Light Source and Ritsumeikan University.

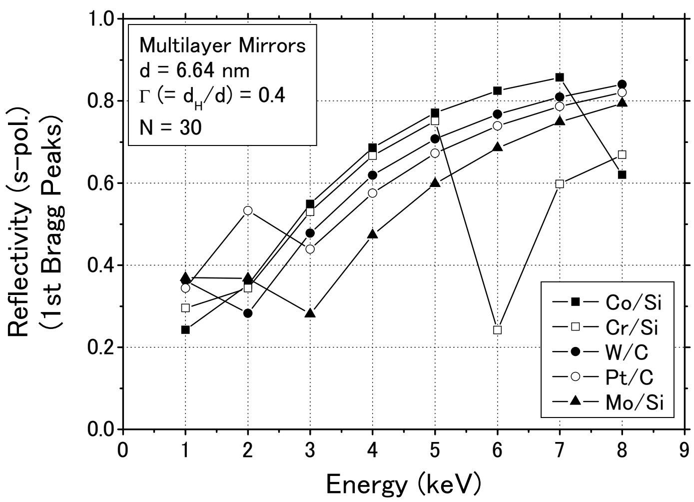

Fig. 1 Calculated 1st Bragg peak reflectivity of multilayer mirrors. Multilayers are assumed to have ideal structures.

Analytical designing of two-aspherical-mirror anastigmats permitting practical misalignments for soft-X-ray imaging

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With use of soft X-ray multilayer mirrors of several tens % reflection at normal incidence, practical microscopes with a laboratory source have been expected to be realized as an alternative to the conventional zone-plate microscope, which requires a narrow beam of synchrotron radiation available at limited location and machine-time. Historical Schwarzschild optics has also been demonstrated for imaging microscopes for soft X-rays.[1-2) However, the resolution still stays at a few micrometer range.

Although the Schwarzschild optics has good characteristics of small aberration, it has a practical drawback in high alignments accuracy required. As Horikawa[1)] has pointed out, for imaging by a soft X-ray of 3.98 nm in wavelength, a permissible alignment error of the Schwarzschild mirrors falls within 300 nm for achieving diffraction limit imaging. Such a high sensitivity to misalignments can be the dominant difficulty for implementing the mirror optics of several cm in diameter and several tens cm apart at sufficient stability under various disturbances such as temperature drifts and mechanical vibrations.

The most promising solution to overcome this difficulty would be to seek for low alignment sensitivity configuration allowing larger misalignments by extending the spherical mirrors to aspherical, since such mirrors are now commercially available. For versatile designing to find new solution groups, an analytical method should be much more useful than a standard computer designing based on ray tracing and numerical optimization. Closed-form equations usable for this purpose to search for two-aspherical-mirror anastigmats have been previously treated.[3)] The equations were found impractical however, because the solution groups were described by one variable indirect to practical design parameters. Therefore, the pupil obstruction needs to be calculated separately, which lacks insight to find practical solutions of high throughput essential in the soft X-ray optics composed of the partial reflection mirrors.

In this presentation we propose a new analytical method of designing based on new practical equations formulating aberrations for searching two-aspherical-mirror anastigmats in terms of the pupil obstruction of the optical systems. Then we introduce additional aberration terms caused by a slight misalignment to discuss the misalignment sensitivity of the solution groups. These formulations are then used for searching the anastigmats groups of soft X-ray microscopes respecting low sensitivity to misalignments and a large field of view.

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Analytical application of multilayer X-ray optics

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To characterize the structural and morphological parameters of compact materials and thin films X-ray diffraction and X-ray reflectometry are widely used both on laboratory X-ray sources and on synchrotrons. The required beam characteristics which mostly depend on the real sample can be realized by various X-ray optical systems that produce either low divergence (high resolution) or high intensity beams. The actual developments tend to the design of customized systems using one or two dimensional beam shaping multilayer X-ray optics, multilayer monochromators or the combination of multilayer optics with other types of X-ray optics. A close interrelation of design, deposition, characterization and application is required to produce these tailored systems. To fabricate either high reflectance or tailored resolution multilayer X-ray optics complementary high precision deposition technologies (MSD, LA-PLD and DIBD) with a reproducibility and long term stability in the sub-nanometer range have to be installed.

Parallel beam X-ray optics exhibit favour advantages for X-ray diffraction investigations of multilayers and single crystals by means of grazing incidence geometry. These parallel beam X-ray optics overcome a number of experimental problems, influence of sample displacement on accurate angle-positions of X-ray reflections first of all. Some examples of Rietveld refinement of the structure models of rare-earth-boron-carbides yielded clear evidences of a high potential of parallel beam X-ray optics also for collection of powder diffraction data intended to Rietveld analysis. With a low beam divergence, which can be realized by coupling of parallel beam multilayer X-ray optics and Channel Cut (CC) crystals a total layer stack thickness of more than 500 nm can be resolved by X-ray reflectometry (Cu Kα radiation).

Recently 2 dimensional detectors have reduced the measuring time in comparison to conventional point detectors. It allows the characterization of small organic crystalline samples. These techniques require 2-dimensional X-ray optics like Kirkpatrick- Baez (K-B) and side-by-side (Montel) arrangements or paraboloidal or ellipsoidal multilayer optics.

Optical design of a laboratory spectro-reflectometer for multilayer imaging optics in the water window region

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We have designed a laboratory spectro-reflectometer for multilayer imaging optics for a quick improvement of our multilayer deposition technology in the water window region. The main specifications are:

1. The apparatus is shorter than 4 m,
2. The resolving power is larger than 1,000,
3. The incident beam to the test multilayer has a spherical wave front.

Spec 1, 2 and 3 are required by our laboratory size, the spectral width of a several hundred layers stack, and the angular width of that, respectively. From spec 1 and 2 a monochromator of Monk-Gillieson type using a varied line space grating, which enables a high resolution with a constant length was chosen. The central groove density is 1200 mm^{-1} and the varied line space parameters are optimized at 400 eV. From spec 3 the exit slit length is limited to 500 μm, which corresponds to angular width of $\Delta\phi = \cot\phi/1000$ from a test multilayer of 50 mm radius of curvature at $\phi = 5$. The goniometer is translatable depending on the radius of curvature of the test multilayer. A troidal mirror is used as a converging mirror for a high throughput. Because the sagittal focus is better than the tangential the configuration where the meridional plane of the mirror is perpendicular to that of the grating was chosen for a higher resolving power. The resolving power determined by a 40 μm entrance slit width, a 25 μm exit slit width and an aberration of a troidal mirror of a 250 mm · 25mm optical area was estimated as 1,300 at 400 eV. Ni was chosen as the mirror and the grating coatings for a high reflectance.

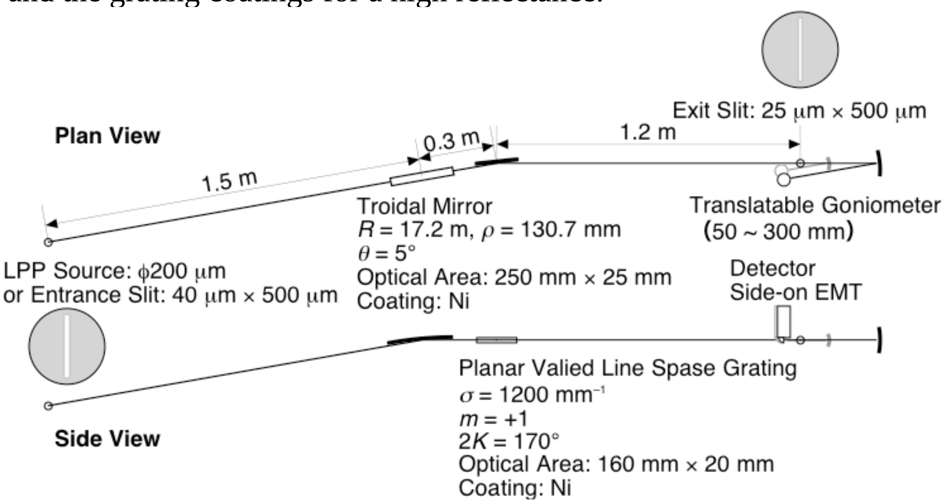

Fig. 2. Schematic illustration of spectro-reflectometer chambers.

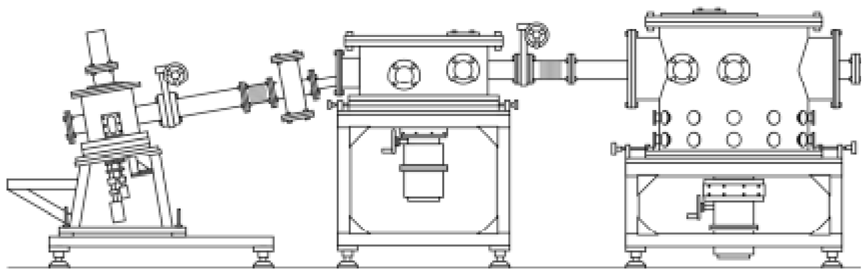

Fig. 1. Design of a spectro-reflectometer for concave multilayers.

The Period Thickness Distribution on the Spherical Substrates Measured with Si Wafers Assemblies

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Introduction

We are developing a soft X-ray microscope [1] and an interferometer [2] composed of spherical multilayer mirrors, which need almost flat period thickness distribution. In deposition, the moving shutter [3] is used for achieving the desired distribution.

For measurement of period thickness distributions on spherical multilayers, the X-ray diffractometry (XRD) has been difficult. One solution would be the normal incidence EUV reflectometry [4]. We have developed another method to measure deposition rates on spherical substrates using a Si wafer assembly making XRD applicable. Small pieces of Si wafers are aligned tangential to the sphere and are supported by a polyhedral holder like a concave "mirror ball".

Experiments

The Si wafer assembly of a 300 mm radius of curvature is shown in Fig. 1. The measurement positions were x = –45, –25, +00, +16 and +36 mm. The ion beam sputtering system was used for deposition with Ar sputtering gas. The designs of the Mo/Si multilayer were D ~ 6.55 nm, γ ~ 0.40 and N = 40. Before the deposition of the concave substrate, the moving shutter was programmed to make the distribution of the assembly flat. Fig. 2 shows the period thickness distributions that normalized by the designed 6.55 nm. "Pre-deposition" and "post-deposition" mean the depositions on the assembly just before and after the concave substrate. The period thicknesses of the concave mirror were measured by EUV reflectometer of BL-12A, the Photon Factory. The period thickness distributions on the assembly were almost flat of 6.55 nm. That on the concave substrate was success fully flat within an error of ±0.3% with the same program of the moving shutter in "pre-deposition", while the thickness level was unexpectedly 0.4% lower.

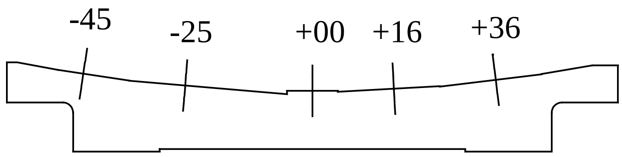

Fig. 1 The Si wafers assembly of a 300 mm radius of curvature. x = –45, –25, +00, +16, +36 were measurement position.

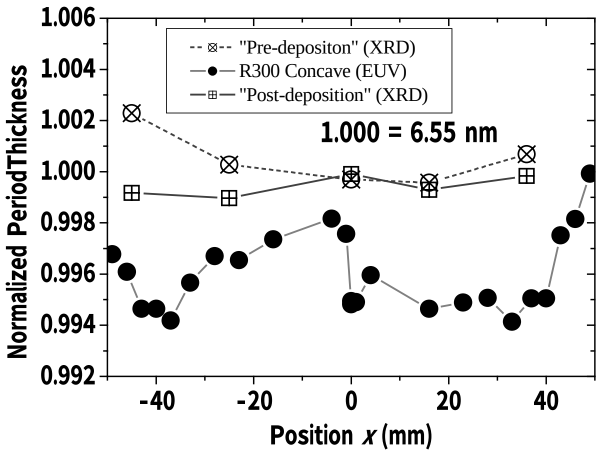

Fig. 2. The period thickness distributions of the Mo/Si multilayers on the concave mirror and the Si wafer assembly.

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Multilayer collector optics for high-power LPP sources

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Key words: EUV, EUVL, Mo/Si, graded multilayers, collector mirror, LPP source.

The high output power of an EUV source at 13.5 nm and the source and collector lifetime can be regarded as one of the major challenges of EUV lithography development today. Current collector mirror concepts are mainly based on the source geometry. Grazing incidence Wolter collectors are commonly used for discharge produced plasma (DPP) sources while multilayer collector mirrors are finding applications for LPP sources. At the Fraunhofer IOF Jena different technologies for the precise deposition of high-reflective and laterally graded multilayers on curved collector substrates were developed in the past.

Figure 1 shows a coated π sr collector mirror for high-power LPP sources. The ellipsoidal mono crystalline silicon substrate has an outer diameter of 250 mm and a lens sag of 40 mm. The Mo/Si multilayer coating was deposited with the EUV sputtering system NESSY. The angles of incidence vary from normal incidence at the mirror center to about 22 degrees at the mirror edge. In order to meet the Bragg condition at every position of the mirror surface a one-dimensional lateral film thickness gradient had to be realized. A deviation of 0.05 nm from the design wavelength of 13.5 nm represent a maximum period thickness error of $\Delta d/d = 0.37$ %. Thus, the absolute period thickness error that can be tolerated within the multilayer stack is $\Delta d = 0.025$ nm. Figure 2 shows the ideal and measured period thickness as a function of the collector mirror radius. The measured peak reflectivity of the collector mirror varies from R = 67.7 % at 13.5 nm in the center to R = 64.7 % at the edge of the mirror.

Fig. 1: Mo/Si coated collector mirror for high-power LPP sources.

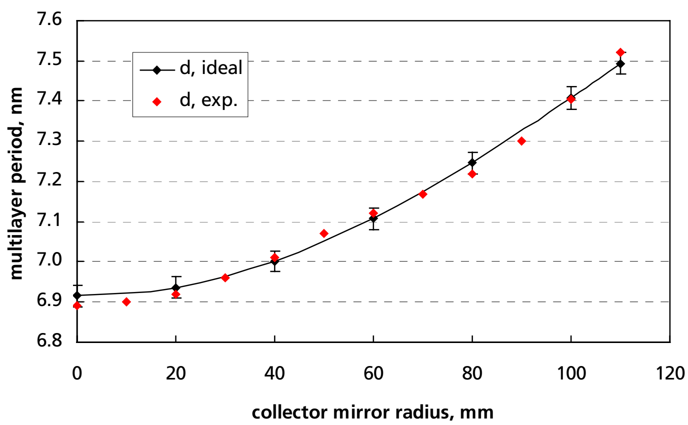

Fig. 2: Lateral thickness gradient on EUV collector mirror.

MO/SI MULTILAYERS WITH RUTHENIUM INTER-LAYERS: A THERMAL STABILITY STUDY

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Recent advancements in high-power EUV source technology for next generation lithography, require that multilayer mirrors optics at the collector level can operate at temperatures as high as 400°C. For this applications, as well as for the components like monochromators, focusing mirrors and polarimeters to be used with intense synchrotron beams, not only good in-band reflectivity but also thermal stability is required to ensure performance. Multilayer systems consisting of pure Molybdenum and Silicon are known to have high EUV reflectivity at normal incidence, but these multilayers are stable only up to about 100°C. As a matter of fact, Mo-Si interdiffusion and $MoSi_2$ formation readily starts above 150°C, leading to destruction of mirror structure and performance. The insertion of nanometric inter-layers has proven to be effective to prevent interdiffusion of Mo and Si atoms on specific interfaces. Proper inter-layer materials have on one side to promote formation of stable compounds, assuring thermal and chemical stability, correct periodicity and Γ ratio; on the other side, in order to optimize EUV reflectivity, candidate materials have to present suitable optical constants. In this work, thermal stability of Mo/Si multilayer with nanometer Ruthenium inter-layer is investigated. In recent years Ruthenium has gained incresing attention as candidate material for both grazing and normal incidence EUV mirrors, due to the combination of optimal optical properties –it has optical constants very close to those of Mo- and chemical stability.

Mo/Si based multilayers have been deposited by rf-magnetron sputtering, with Ru inserted at interfaces following different combination stacks. Samples have been subjected to thermal treatments up to 400°C. EUV reflectivity measurements show that 80% of initial reflectivity is still present after thermal treatments. The effects of thermal treatments on multilayer structural parameters have been investigated by X-Ray Reflectivity: only a small contraction of multilayer period is reported. Phase formation and crystallography have been inspected by means of X Ray diffraction. Moreover, excitation of X-Ray standing waves inside the multilayers allowed investigation of interface compound formation.

Fabrications of Small D-Spacing W/C depth-graded multilayers

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Abstract: W/C depth-graded multilayers working in the grazing incident angular region (0.8-1.2°) at Cu-Kα line (λ=0.154 nm) were designed with three different optimization methods: (a) simplex algorithm, (b) the method based on the combination of analytical and numerical optimization, and (c) simulated annealing algorithm. The multilayers optimized by first two methods have centric layer thickness distributions of tungsten and carbon in the range between 1 nm and 5 nm, whereas the multilayer optimized by the method (c) has bipolar layer thickness distribution oscillating from 1 nm to 5 nm. Although the layer thickness distributions are different, the calculated reflectivity curves are similar. After fabricating these three W/C multilayers using a DC magnetron sputtering, a small-angle X-ray (0.154 nm) diffraction was used to analyze their reflectivities. The experimental results suggest that the angular regions are all drifting to the large angle and the deviation of reflectivity curve is larger for the layer thickness distribution optimized using method (c) whose layer thickness changes abruptly, which indicates that its fabrication doesn't coincides with the design aim. i.e., the stabilization of fabrication varies with the layer thickness. In order to control layer thickness accurately, a series of W/C periodic multilayers were investigated, whose period thicknesses vary from 1nm to 5 nm with increment of 0.5 nm. By fitting to reflectivity curves of these periodic multilayers measured by XRD, we found that the calculated thickness of tungsten and carbon layer abnormally deviates from their nominal layer thickness, especially for the ultra-thin layer around 1 nm. These deviations can be amended using the following two methods:

Method 1: Using the experimental results of periodic multilayers, the deposition rates in different layer thicknesses can be calculated. From sigmoidal fitting of the deposition rate versus layer thickness, the deposition rates as a function of the layer thickness could be determined;

Method 2: The deposition rate can also be determined using the formula: $d=v\times t+\Delta d$, where d is the layer thickness; v and t are the deposition rate and time; and Δd is the thickness change (contraction or expansion), not inter-diffusion. Assuming that the deposition rates of both materials and thickness change are constant in this model, Δd and v can be determined from linear regression of d versus t. In our experiments, 0.41 nm expansion of tungsten layer and 0.40 nm contraction of carbon layer were found.

These two methods are both effective. After modification, the layer thicknesses of the non-periodic multilayer have been well controlled, and the experimental results coincides with our design aims.

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Development of beam splitter for EUV microscope

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We advanced the development of beam splitter for EUV region since 1992, and the fabrication of Mo/Si multilayer beam splitter which has the size of 10 mm × 10 mm and the flatness of 2 nm was succeed according to optimization of stress condition. Now, we develop large-aperture beam splitter that is required to construct of phase-shift EUV interferometer.

The defect-free multilayer reflective mask is one of technological requirements for the EUVL achievement. It is necessary to make to 0.003 or less defects/cm^2 of 30 nm in EUVL. Concerning the defect-free mask making, we have been developing an EUV phase-shift microscope, which can inspect the amplitude defects of 20 nm in size and the phase defects of 0.03 nm in height. For this purpose, phase-shift EUV interferometer with Schwarzchild optics and have to be developed.

Table 1 shows the specification of the beam splitter for EUV Mirau Interferometer. And Fig. 1 shows the configuration of the process of beam splitter fabrication. In order to control stress easily, the process which carries out back etching previously was chosen. In this paper, the progress of beam splitter fabrication will be shown.

Table 1 Specification of beam splitter.

Wavelength	13.5 nm
Incident angle	17°
Multilayer	Mo/Si
Top layer	Si
Periodic length	7.3 nm
Aperture	15 mm□
Flatness	2 nm

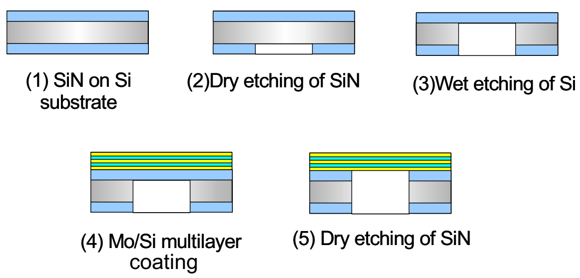

Fig. 1 Configuration of the process of beam splitter fabrication

Post Deadline Abstracts

Development of ellipsoidal broadband multilayer mirror for a wavelength region from 15 nm to 18 nm

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A graded and broadband Mo/Si ellipsoidal multilayer mirror has been developed. The purpose of this ellipsoidal mirror is to collect the fluoresced EUV (15.5nm and 16.5nm) from an illuminated copper by 13.9nm x-ray laser. The surface of the ellipsoid is shown as the equation of $X^2/1285^2+Y^2/418^2=1$. It means that the distance between the sample and the mirror is 70 mm, and the distance between the mirror and the focus point is 2520 mm. Our designed mirror has following two features: (1) the flat reflectivity curve around the wavelength region from 15 nm to 18 nm, (2) same reflectivity curve on all mirror point. To satisfy the feature (1), the depth-graded multilayer, which is called “broadband” multilayer mirror, is designed. To satisfy the feature (2), the periodic length of multilayer varied along the radius, which is called “graded” multilayer mirror, is designed. In the case of this ellipsoidal mirror, normal incident angles change from 0° to 20° along the outer of the substrate. So, the periodic length on the edge is 1.07 times longer than that on the center.
These multilayers were fabricated by magnetron sputtering. Figure 1 is a photograph of a graded and broadband Mo/Si ellipsoidal multilayer mirror. The broadband multilayer on Si wafer and on ellipsoidal substrate have the reflectivities of about 20% and about 15%～22% at a wavelength region from 15nm to 18nm, respectively (Fig. 2). These results show that this ellipsoidal mirror is useful for the collects the fluoresced EUV.

Figure 1: Photograph of ellipsoidal graded and broadband Mo/Si multilayer mirro. The substrate has the diameter of 100mm, the thickness of 30mm, and it is made of Zerodure.

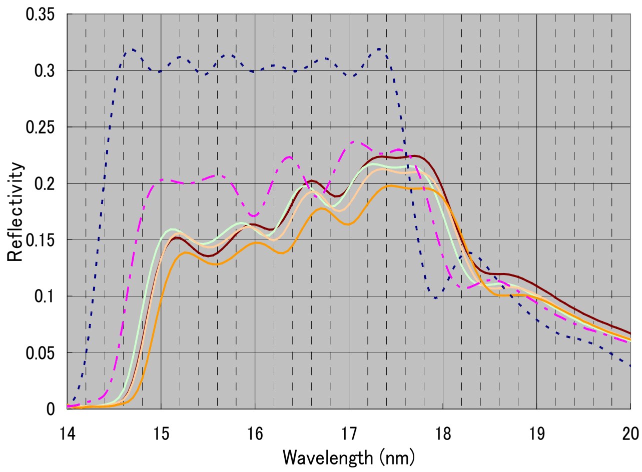

Figure 2: The measured reflectivities and designed reflectivity (highest dotted line) of broadband Mo/Si multilayer.

Poster Session 2
Wednesday March 15th, 2006

Abstracts

Development of Mo/Si multilayers mirrors for EUV Lithography

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Due to their high normal incidence reflectance achieved around 13.5 nm, Mo/Si-based multilayer mirrors have been widely studied in last years, mainly for applications in EUV Lithography.
In this work, Mo/Si multilayers were deposited by DC/RF magnetron sputtering. We first optimised Mo/Si lateraly graded thicknesses to take into account angle of incidence variation of the different rays on a 190 mm-diameter EUV optic, using a deposition technique that consists in variing the substrate velocity when it goes above the sputter sources. We obtained a thickness uniformity better than ±0.5% along the diameter of the optic (Fig. 1). This multilayer was also characterized at-wavelength using synchrotron radiation reflectometry at ALS-Berkeley.
The second part of this work deals with the introduction of SiC barrier layers in Mo/Si multilayers. The introduction of a third material as barrier layer at both interfaces in Mo/Si multilayers has been studied before to improve performances of such multilayers.[1] In this work, soft x-ray reflectivities were calculated to optimise SiC thickness, in the aim to study experimental effects of the barrier layer thickness and to compare it to the litterature. Then, annealing effects on both the reflectivities and layer structures of Mo/Si multilayers with and without barrier layers using hard x-ray ($\lambda = 0.154$ nm) grazing reflectometry will be discussed (Fig.2). These multilayers were also characterized at-wavelength on a new EUV reflectometer at CEMOX (Centrale d'Elaboration et de Métrologie d'Optiques X - Orsay). This reflectometer, developed to characterize EUV optics, allows us to be more self-sufficient with respect to synchrotron beam lines, which remains nevertheless the tool of reference for EUV optics characterization.

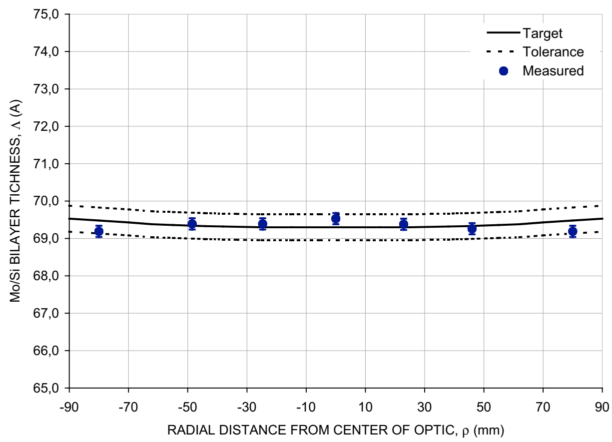

Fig. 1. Multilayer period versus diameter of the optic measured using hard x-ray grazing reflectometry

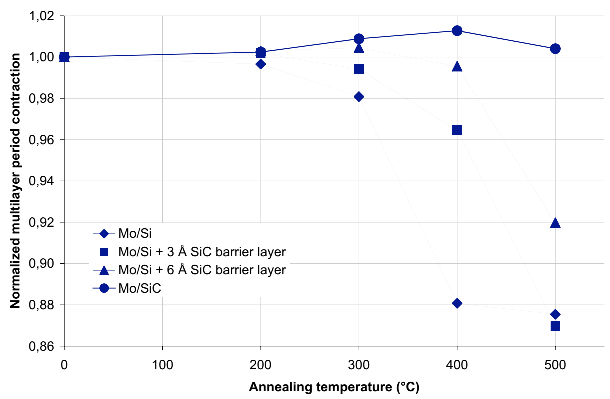

Fig. 2. Normalized multilayer period contraction versus annealing temperatures for different multilayer structures

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Multilayer Laue Lenses for Hard X-ray Nanofocusing*

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A Multilayer Laue Lens (MLL) is a new type of linear zone plate consisting of sectioned planar depth-graded multilayers in transmission diffraction geometry for nanometer-scale focusing of hard x rays [1-4]. For x rays diffracted by each and every layer to add "in phase" at the primary focus, the multilayers need to have good mechanical and thermal properties, sharp interfaces, and accurate layer placement. The multilayer also involves thousands of layers with correlated thicknesses varying from a few nm to tens of nm. In this presentation, the material system of dc magnetron sputtered WSi_2/Si multilayers is compared with that of W/Si in terms of growth characteristics, interface sharpness, and film stress. Multilayers with precise zone-plate structures have been successfully fabricated using the WSi_2/Si system. Layer thicknesses and layer positions of zone-plate multilayers were analyzed with SEM images. The growth-rate decay during prolonged depositions was studied using x-ray reflectivity measurements on test periodic multilayers grown before, during, and after a zone-plate multilayer growth. An iterative process was used to perfect the growth with predetermined growth-rate corrections to achieve a desired zone-plate multilayer structure. A nearly perfect multilayer consisting of 728 layers with 12.43-μm total thickness and 10-nm outermost zone width has produced a diffraction limited line-focus of 30.6 nm with an efficiency of 44% at an x-ray energy of 19.5 keV.

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Multilayer optics with spectral purity layers for the EUV wavelength range.

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Being a quasi-monochromatic imaging method designed for a narrow wavelength band around 13.5 nm, Extreme Ultra Violet (EUV) projection lithography systems have to include spectral aspects of the light source and the photo-resist in the band outside the 13.5 nm range. Most EUV light sources so far spectrally characterized have shown considerable spectral intensities in the VUV, or 'out-of-band' wavelength range [1]. Since candidate photo-resists exhibit a high sensitivity to out-of-band radiation, this imposes strict requirements for the spectral purity of the light coming from the illumination and projection optics.
The Mo/Si multilayers that are currently being developed as reflective optics for EUV projection lithography systems have high reflectance and yield high optical throughput for the 13.5 nm wavelength region. However, it is known that they simultaneously exhibit a high out-of-band reflectivity, especially in the 100-200 nm wavelength region where photo-resists are highly sensitive.
To increase the spectral purity, out-of-band reflectance should therefore be suppressed, without a dramatic reduction of the in-band reflectivity. For this purpose, a new multilayer design was developed that includes an enhancement of the spectral purity. This system has been optimized to suppress the 100-200 nm wavelength region. Reflectivity measurements performed at the BESSY synchrotron radiation facility in Berlin clearly show a reduction of the reflection of out-of band radiation by more than 80%, while the in-band reflectivity only decreases by 5%, thus significantly improving the spectral purity. Further reduction in the out-of-band radiation is expected in future systems.

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Interfaces in Ni/C and Ni/B_4C Multilayers

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Interference multilayer mirrors have become an indispensable part of instrumentation in astronomy, lithography, plasma diagnostics, at synchrotron storage rings and in other fields. Compositionally sharp and geometrically smooth interfaces are required for high reflectivity. Interface roughness results from the substrate and growth process itself while thermodynamic characteristics of the constituents may cause their mixing at the interfaces. For nanometer-scale period multilayers it is useful to utilize a combination of mutually immiscible materials to reduce the mixing at the interfaces as it was demonstrated in the case of compound layers like B_4C to stabilize carbon-based ML structures. Recently, thin B_4C interlayers were applied as diffusion barriers for Mo/Si and Sc/Si systems [1]. In all these material couples, an increased stability of interfaces was observed. However, immiscible material combinations could lead to collapse of the multilayer and formation of a granular like structure at elevated temperatures.

In this work, we present a comprehensive characterization of Ni/B_4C interfaces in terms of the intermixing, morphology, geometrical roughness and its replication completed by an inspection of the internal layer structure in the as-deposited state and after a heat treatment. For comparison, a similar study of Ni/C multilayers was performed. From the X-ray reflectivity and reciprocal space map of a particular multilayer, the basic characteristics of the multilayer stack such as multilayer period, individual layer thickness and effective interface roughness, the geometrical interface roughness and its correlation properties were obtained. The study is completed by the inspection of the structure inside the layers using the transmission electron microscopy and X-ray diffraction.

The Ni/C multilayer exhibited a gradual increase of the ML period from 3.15 nm to 3.52 nm with increasing annealing temperature up to 300°C when the multilayer structure got heavily disturbed, this increase being attributed to the graphitization reported for the Ni/C pair [2]. The TEM studies showed that the multilayer decay was driven by the growth and coalescence of fcc Ni grains present in Ni layers after deposition. This evolution was also responsible for an increase of the lateral correlation length and a loss of the vertical correlation of the interfaces due to the annealing. The width of the intermixed regions judged from the difference between the effective and geometrical interface roughness was rather stable before the multilayer decay indicating that diffusion of C into Ni took place mainly along grain boundaries. Ni/B_4C multilayer with period of 1.59 nm had very smooth interfaces with 0.28-0.3 nm roughness so that a higher number of periods was necessary to measure the reciprocal space map reliably. An annealing showed a better thermal stability of Ni/B_4C interfaces in comparison with Ni/C ones in spite of the ultrashort multilayer period. It is obvious that grain boundary diffusion is hampered in presence of the compound layers. Amorphous structure of ultrathin layers after deposition may also play some role in the enhanced thermal stability.

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Determination of the optical constants of rare-earth metals and carbon in the EUV spectral region 18-400 eV.

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The study of EUV optical constants provides information, which is necessary for the design of reflective multilayers used in synchrotron radiation devices, optics for EUV lasers, X-ray astrophysics and many other applications. Particularly important are spectral regions near the absorption edges of elements, where the reflection of multilayers is the highest.

Our determination of the EUV optical constants of La, Tb, Gd, Nd and amorphous C at photon energies 17-400 eV was performed by the method described in reference [1]. For this aim three thin (about 10-20 nm) and three thick (about 50-150 nm) films of each metal were deposited on silicon photodiodes and capped with a thin layer of Si or B4C. For carbon all films were thicker by a factor of 7, because of its high transparency. Transmission measurements were performed with the National Synchrotron Light Source beamline X24C at Brookhaven National Laboratory. Their treatment gave the optical constants of the elements that are free from the effects of contamination and oxidation in the atmosphere. The last detail is especially important for rare-earth metals, which are oxidized easily in the atmosphere. We also performed the first-principles calculation of the electronic structure and gave on this basis the interpretation of the near-edge absorption features. The measured optical constants are planned for use in the design of reflective multilayers intended for solar studies at wavelengths near 60 nm and for the imaging of carbon-based materials in the spectral region 4.4-5.0 nm.

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Designing of multilayer mirrors for metrology of EUV sources

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Development of EUV lithography tools demands characterization and comparison of available EUV sources in respect of the emitted radiation power. Emission spectrum of a EUV source is typically wide and extended generally from several nm to several tens nm. At the same time, the total reflectivity of an optical system consisting of up to 11 Mo/Si multilayer mirrors is differed from zero within a narrow spectral interval of about 0.6 nm width centered at $\lambda = 13.5$ nm. Therefore, for metrology applications it is necessary to filter in-band radiation power out of the whole emission spectrum of a source.

We analyzed a possibility of designing of a depth-graded multilayer structure for using in the metrology of broad band sources. The mirror operating together with transmittance filter should provide the same form of the reflectivity peak as that after reflection from 11 periodic Mo/Si multilayer mirrors and as small reflectance as possible outside the peak to guarantee the necessary spectral purity of a reflected beam. The efficiency of filtering is characterized by the ratio of out-band radiation power to in-band one $\chi = \int\limits_{\mathrm{out-band}} R(\lambda)d\lambda / \int\limits_{\mathrm{in-band}} R(\lambda)d\lambda \cdot 100\%$, which should be less than 1% for practical applications. For comparison, the parameter χ exceeds 20% in case of a periodic mirror.

We demonstrated that there are several factors leading to an enhanced efficiency of filtering of in-band radiation from the whole emission spectrum. Among them (a) the use of multilayer structure with the reduced reflectance from upper and lower bi-layers, (b) the use of silicon containing transmittance filter (such as $ZrSi_2$ or $MoSi_2$) cutting effectively short-wavelength radiation at $\lambda < 12.4$ nm, (c) increase of the filter thickness, and (d) increase of the number of bi-layers constituent a multilayer structure. Combining all these factor we designed multilayer mirror with extremely small χ-ratio (0.017% only). The total transmittance of the mirror and the filter is $RT \approx 3\%$, what is quite practicable. Increasing parameter χ up to 0.15-0.25% allowed us to design multilayer structures providing the total transmittance RT more than 10%.

We analyzed different physical and technological factors influencing the optical quality of the designed multilayer mirrors (impossibility of deposition of ultra-thin layers, inaccuracy in density and optical constants of materials constituent multilayer mirror, interfacial roughness, and so on) and demonstrated that the crucial factor is random layer fluctuations, which thereby should not exceed ± 0.02 nm.

Results of the first experiments on deposition of depth-graded multilayer mirrors are presented.

Depth graded Pt/C multilayers for X-ray telescope

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High throuput telescope is essential instruments for astronomy. In X-ray region, it is also needed for high sensitivity observation. In hard X-ray region, total reflecttion which used in previous X-ray telescope requires extremely grazed incident angle. It means multilayer X-ray mirror must be needed for hard X-ray telescope.

We developed depth graded multilayer for hard X-ray telescopes. For astronomical use, X-ray optics was requires wide energy band and high through-put. In this point of view, Performance of the X-ray reflector is most important for the X-ray telescope. Depth graded multilayer make us possible to extend the energy band to hard X-ra region above 10 keV, in contlast that total reflected mirror, used in previous X-ray telescope, limit the eneryg band of telescope in soft X-ray band. We try to extend energy band of X-ray telescope up to 70 keV using Pt/C multilayers. Platinum is one of the most suitable matelial for X-ray telescope, becase it is very stable in chemical and energy of K absorption edge is higher than energy of ^{44}Ti nuclear γ-ray, which is key of the mistery of supernovae.

We tryed to optimize design of the depth graded multilayers for X-ray telescope. It has to have high reflectivity for high through put and wide energy band, for wide band observation and field of view of telescope. Futhermore, small number of layer pairs is required for mass production of reflector, we need about thousand of reflectors for a telescope.

We designed depth graded multilayer by piling up several constant-d multilayers. Periodic length of each constant-d multilayer was become small from surface to bottom layer. Interval of Bragg energy of each multilayer is kept constant. Design parameters are interval energy and number of layer pairs of these multilayers. We designed 12 depth graded multilayers according to its incident angle, $0.1 - 0.3$ degree. we achieved high reflectivity up to 70 keV using these depth graded multilayers.

We are trying to improve the reflectivity of multilayers by reduction of interfacial roughness. We introduced ion beam sputtering system, it can sputter in high vacuum atmosphere comparing with DC magnetron sputter, it reduce the contamination of argon.

XUV mirror fabrication for attosecond optical science

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Among X-ray and extreme ultraviolet (XUV) light sources able to produce increasingly short, coherent and intense pulses, high order harmonics (HH) generated in rare gases are currently the most promising way to generate attosecond pulses. The manipulation and transport of these pulses requires the development of dedicated optics for reaching specific characteristics in terms of amplitude but also in terms of phase control. Indeed it has been shown that attosecond pulses obtained from laser-driven high-harmonic generation sources present an intrinsic chirp that has to be compensated in order to take full advantage of the temporal resolution. We here present two different multilayer designs for chirp compensation of attosecond pulses.

The first design involves a combination of two periodic multilayers including Mo, Si and B_4C within each period. The thickness of the materials in the superimposed B_4C/Mo/Si multilayers was optimized in order to reach a high reflectivity in the 25-40 nm wavelength broadband. The multilayers were deposited by using the magnetron sputtering technique described elsewhere for the fabrication of trimaterial systems [1]. The reflectance of the stacks were measured on the BEAR line of the ELETTRA synchrotron facility in the spectral range 20-40 nm and compared to calculations. A bandpass of 12.6 nm and a reflectivity of 20% around λ=34 nm could be reached. A high order harmonic source developed at Lund Laser Center was used to measure the phase variation induced by reflection on such a mirror. The first experiments [2] could demonstrate that this type of broadband multilayer mirrors should enable to temporally compress the reflected attosecond pulses.

Another concept appropriate for the spectral region 12-20 nm consists in using aperiodic stacks of Mo/Si thin layers. Spectral reflectivity and phase were computed for aperiodic multilayers by using an algorithm described in [3] which takes into account the HH intrinsic chirp and the variation of the optical constants with wavelength. Four aperiodic Mo/Si multilayers were calculated and deposited by using the ion beam sputtering chamber developed for the deposition of periodic multilayers for XUV solar imaging applications [4]. The thickness of Mo and Si layers were controlled by using a quartz balance and were calibrated by depositing a series of periodic multilayers in order to evaluate the interface effects. The measurements of EUV reflectivity of the mirror carried out on the XUV reflectometer at CEMOX (Centrale d'Elaboration et de Métrologie des Optiques X-Orsay) and on the ELETTRA synchrotron facility at Trieste allowed us to conclude that despite a wavelength shift and a reflectance loss the properties of chirped mirrors satisfied the requirements of attosecond compression.

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W/C multilayered laminar-type holographic grating and its application to a high efficiency grazing incidence monochromator for the 1-8 keV region

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Progress in grating and crystal monochromators has extended their energy regions and a portion of the energy region of 1 - 8 keV has been accessible to both gratings and crystals. However, the entire energy region has not been easily accessed solely by either type of optic. Crystal monochromators provide good monochromaticty but the integrated diffraction efficiency is limited by the small cross section due to the large lattice constant. Also crystals having large lattice constants are sometimes weak against heavy heat load and this property prevents them from applications using bright synchrotron radiation sources. In grating monochromators grazing incidence angles are required to overcome low efficiencies which invites larger loss of the incoming flux due to the narrowing of the acceptance angle. Diffraction gratings, especially original (master) gratings, have a proven durability against heat load, and multilayer coatings on the gratings would improve their diffraction efficiencies. Some years ago we proposed a high resolution grazing incidence monochromator consisting of a spherical mirror, a varied line spacing plane grating, and a movable plane mirror. [1] Taking advantage of the flexiblity of this configulation we have initiated the design of a monochromator equipped with a multilayered varied-line-spacing plane grating. Also we have fabricated a W/C multilayered laminar-type plane grating (1200 lines/mm) and evaluated the diffraction efficiency in the energy region of 0.6-8 keV at the SR facilities as well as an X-ray diffractometer at 8.05keV (Fig.1).

In this paper, we describe details of the results of the evaluation of the W/C multilayered grating and the design of the monochromator which employs a W/C multilayered varied-line-spacing grating and movable plane mirror, and a Au coated spherical mirror covering the energy region of 1-8 keV. Also a description is given for the expected performance of the monochromator from the viewpoints of throughput and resolving power.

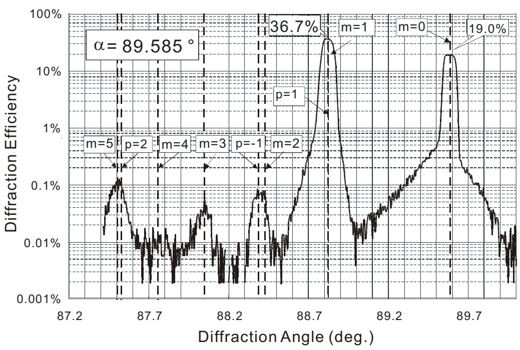

Fig.1. The diffraction efficiency of the W/C multilayered grating at 8.05keV.

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EUV multilayer coatings for the Atmospheric Imaging Assembly instrument aboard the Solar Dynamics Observatory

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The Atmospheric Imaging Assembly (AIA) instrument aboard the Solar Dynamics Observatory is designed to provide an unprecedented view of the solar corona, taking images that span at least 1.3 solar diameters in multiple wavelengths nearly simultaneously, at a resolution of 1 arcsecond, field of view exceeding 41 arcminutes and at a cadence of 10 seconds or better. AIA will produce essential data for quantitative studies of the evolving coronal magnetic field and its plasma. These data will be used to significantly improve the understanding of the physics behind the activity displayed by the Sun's atmosphere, which drives space weather in the heliosphere and in planetary environments. The AIA is composed of four telescopes, each including a primary-secondary pair of mirrors operating at near-normal angles of incidence. Each telescope produces images at two different wavelengths, which is accomplished by two different multilayer coatings acting as Bragg reflectors, deposited across two respective D-shaped areas on each mirror. In this manner, imaging at a total of eight channels -seven in the EUV and one in the UV range- is achieved. In this presentation we are discussing the development and testing of multilayer coatings for the seven EUV channels of the AIA instrument.

Multilayer film parameters for each channel have been uniquely optimized to satisfy criteria for peak reflectivity (throughput), suppression of nearby emission lines, lifetime stability and stress properties. Another crucial requirement for efficient imaging is meeting the wavelength specifications across each multilayer-coated flight optic pair, which in turn depends on precise thickness control of the multilayer thin film across each curved mirror surface. Atomic Force Microscopy measurements were performed on each flight substrate prior to multilayer coating, to determine the roughness in the high-spatial frequency range, which affects the reflectivity of the multilayer-coated mirror. Experimental results on all aforementioned aspects of the AIA flight mirrors will be presented.

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Multilayer mirrors with enhanced thermal stability

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A serious problem of Mo/Si multilayers is the instability of reflectivity and peak wavelength under high heat load. It becomes especially critical at temperatures above 200 °C, where interdiffusion between the molybdenum and the silicon layers is observed.

The development of high-temperature multilayers was focused on two alternative Si-based systems: $MoSi_2$/Si and interface engineered Mo/C/Si/C multilayer mirrors. The multilayer designs as well as the deposition parameters of all systems were optimized in terms of high peak reflectivity (> 60 %) at a wavelength close to 13.5 nm and high thermal stability. Changes of optical and structural properties of samples at elevated temperatures were characterized by small angle X-ray reflection (SAXR), large angle X-ray diffraction (LAXD), normal incidence reflection at the wavelength λ = 13.5 nm and transmission electron microscopy (TEM). Annealing was carried out under vacuum (10^{-5} mbar) at temperatures of up to 800 °C.

Optimization of $MoSi_2$/Si multilayer mirrors resulted in a peak reflectivity R = 41.2 % at the wavelength λ = 13.6 nm. They consisted of amorphous Si and $MoSi_2$ layers. Crystallization of the $MoSi_2$ layers at temperature above 400 °C induced small thermally changes of the $MoSi_2$/Si multilayer properties but they were independent of the annealing time at temperatures below 600 °C. A wavelength shift of -1.7 % and a reflectivity drop of 1.0 % have been found after annealing at 500 °C for 100 hours (Fig. 1). The total degradation of optical properties above 650 °C can be explained by a recrystallization process of $MoSi_2$ layers.

Optimized as-deposited Mo/C/Si/C multilayers presented a peak reflectivity R = 59.6 % at the wavelength λ = 13.5 nm. Thermally induced changes of the optical and structural properties were dependent on both annealing times and temperatures (Fig. 2). The interdiffusion coefficients in Mo/C/Si/C systems have been calculated from the decay rate of the peak reflectivity during isothermal annealing at different temperatures (250, 400 and 500 °C) [1]. The interdiffusion coefficient at 400 °C was found to be around 10^{-26} m²/s.

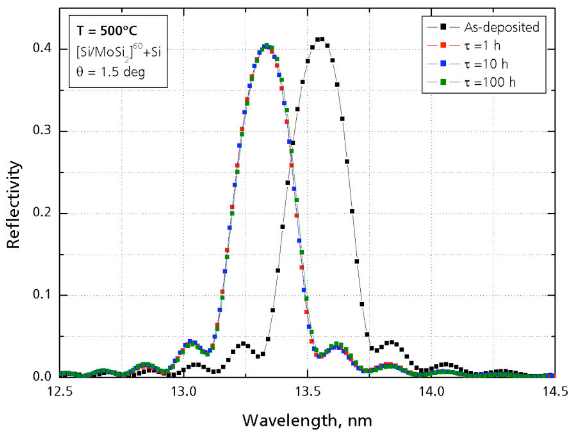

Fig. 1

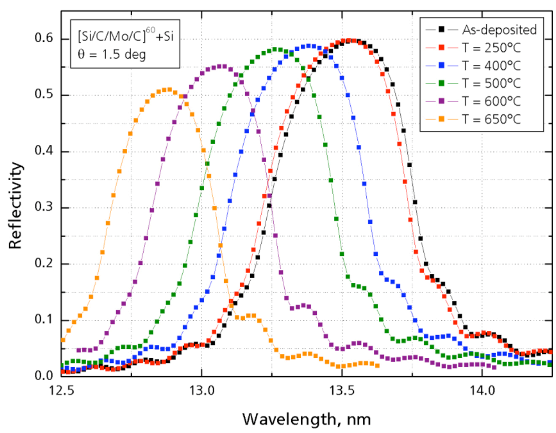

Fig. 2

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EUV Resist Development in NewSUBARU

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Keywords: extreme ultraviolet lithography, chemically amplified resist, exposure characteristics

A novel system for evaluation of EUV resist was installed at BL3 beamline in NewSUBARU synchrotron radiation facility. Figure 1 shows the configuration of this system. This system consists of an optics chamber, an exposure chamber and a sample loadlock chamber. Each chamber has a vacuum system of turbo molecular pump and scroll pump. In the exposure chamber, a high sensitive quadruple mass spectrometer (Model HAL/3F/PIC 501 RC, HIDEN ANALYTICAL Ltd.) which can measure mass number from 1 to 500 of ion species, is used for resist outgassing analysis under EUV irradiation. The main purpose of this whole system is to evaluate the basic physical and chemical properties of various EUV resists candidates, such as to study sensitivity, outgas characteristics, and chemical reaction analysis.

This optical system simulates a 6-mirror imaging system. In the optics chamber, we installed one concave Mo/Si multilayer mirror and two plane Mo/Si multilayer mirrors, looking each other in parallel direction. Incident light is reflected total 7 times, such as one time reflection by concave and six times reflection by plane conjugate mirrors in normal angle before it strikes the sample surface. The total reflectivity spectrum is shown in Fig. 2. The centeroid wavelength is 13.57 nm. The beam size at the sample surface is 4 x 4 mm and we can take five shots for each sample by means of moving the sample in lateral direction. Exposure dose is controlled by the open time of shutter located on the upstream of the optics chamber. The time resolution of the shutter is 11 ms. The flux is 0.33 mW/cm2 on a sample. It takes only 6 s for 2 mJ/cm^2 sensitivity resist. This system is very powerful tool to obtain exposure characteristics. Detailed specification and performance of the system will be discussed in the presentation.

Using this system, it is succeeded to obtain distinctive photoacid generator which has a high acid production yield to reduce the line edge roughness.

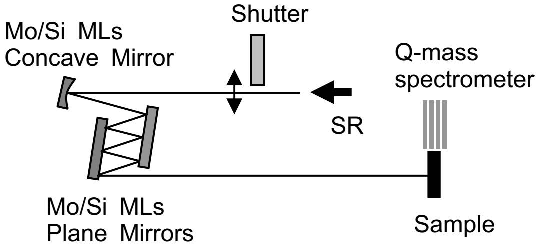

Fig. 1. Schematic diagram of the novel resist evaluation system.

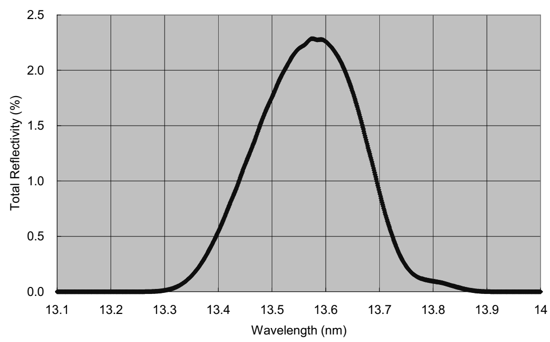

Fig. 2. Total reflectivity spectrum of seven times reflection in the novel resist evaluation system.

The Beam Instability of an ECR Ion Gun and its Similarity to the AC Power Source Fluctuation

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Introduction

We are developing a soft X-ray microscope [1] and an interferometer [2]. They are composed of several multilayer mirrors. The throughputs depend on a single multilayer reflectance and reflection wavelength matching of those multilayers. The periodicity of a multilayer is important for reflectance, and consistence of the period thicknesses is for the matching.

Our ion beam sputtering system has two ECR ion guns (ELIONIX EIG-240). The period thickness is simply controlled by the deposition interval. Because the deposition rate depends on the ion beam intensity, it is important to make the ion beam intensity stable for the periodicity and the matching.

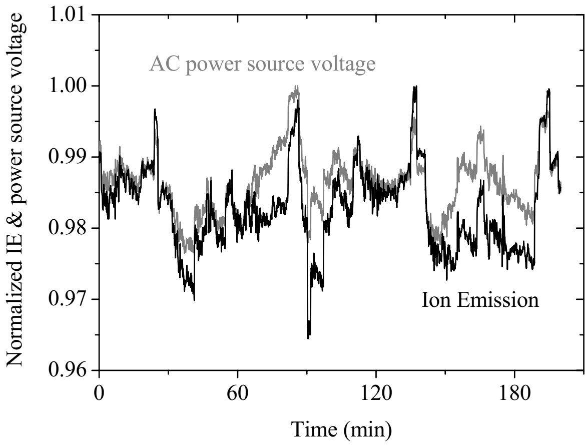

Fig.1 The stability of the AC power source voltage and Ion Emission.

Experiments

An ion emission current (IE), which is an ion current of the accelerator electrode, is used for measurement of an ion beam intensity. A 1400 V accelerator voltage was supplied and Ar was used for sputtering gas. Though the parameters of gas flow rate, magnetic field strength and so on were tuned, the fluctuation of ±1%/hrs were remaining. After a two channel measurement of the AC power voltage and IE, their similarity was found as shown in Fig. 1.

A stabilized AC power source supply was introduced into our deposition system. The AC power source voltage and the IE fluctuations improved to less than ±0.01% and ±0.2%, respectively (Fig. 2). Because the remaining fluctuation of the IE was slow speed component, it is possible to tune the parameters more, those effects had been hidden by the AC power source fluctuation.

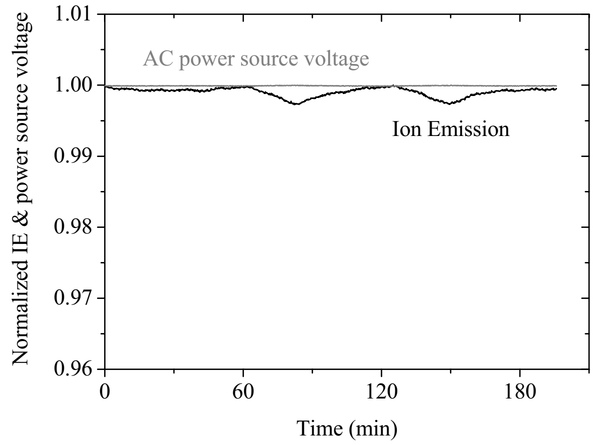

Fig. 2 The improved stability of the AC power source voltage and Ion Emission with stabilized AC power source supply.

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Optimization of boundary structure for soft X-ray multilayer mirrors by an ellipsometric deposition monitor

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In the fabrication of soft X-ray multilayer mirrors, the period thickness of several nanometers is necessary to be controlled precisely over several tens to hundreds period in a multilayer for constructive interference of incident soft X-ray light. The multilayer mirror has to be fabricated at optimized condition for obtaining smooth and sharp interface at every boundary for high reflectance. To study the layer structure formation during ion beam sputtering fabrication of Mo/Si multilayers, we have applied *in-situ* automatic ellipsometer we developed as a deposition monitor [1] with rapid layer-by-layer analysis [2].

In-situ ellipsometric growth curves at the 30th period of Mo/Si multilayers observed at Ar ion acceleration voltages of 1400V and 900V are shown in Fig. 1 (a) and (b). Mo and Si segments form a growth curve of each period up to final layer. When the multilayer is stacked beyond the penetration depth of the incident of He-Ne laser, the growth curve form a closed-loop as shown in Fig. 1. Direction and length of each segment represent the optical constants and layer thickness, therefore layer properties are directly visualized on the complex plane. On every Mo layer deposited at 1400V, downward movement was observed in the early stage just after a target switching. Judging from the characteristic growth curve [3], this movement corresponds to an island structure formation. A silicide layer is likely to be formed on Si with no Mo island growth at 900V. The information obtained by the *in-situ* ellipsometric deposition monitor could be useful in controlling layer thickness and also optimizing fabrication setting to obtain homogeneous and optically isotopic layer growth.

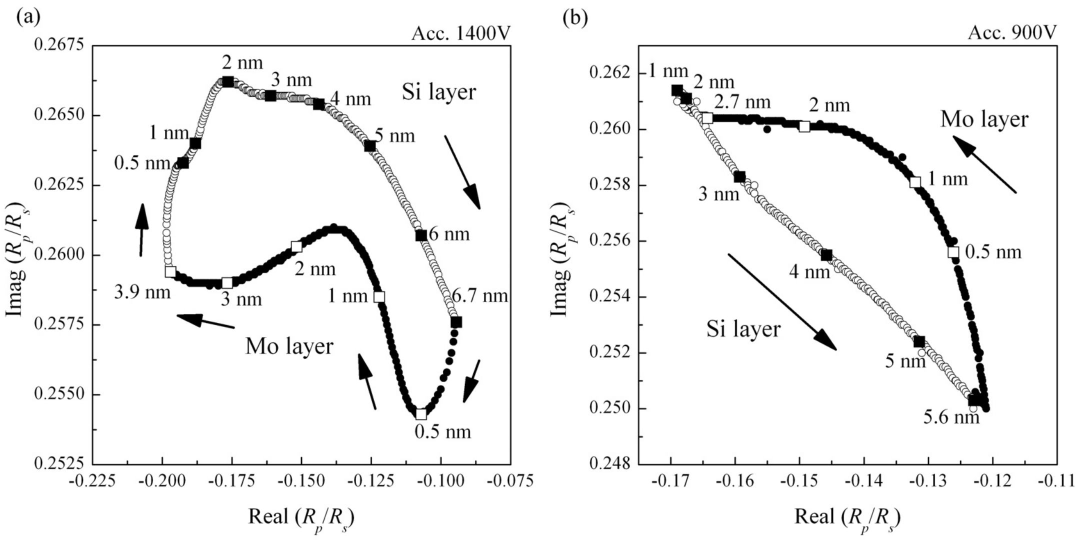

Fig. 1 Close-up views of ellipsometric growth curves of Mo/Si multilayer fabricated at Ar ion acceleration voltages of (a) 1400V and (b) 900V at the 30th period. Solid marks and open marks indicate Mo layer and Si layer, respectively. The square marks indicate thicknesses determined by the layer-by-layer analysis.

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High spectral resolution Mo/Si multilayer at the wavelength of 14 nm

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Abstract: In EUV and X-ray regions, multilayer mirrors can provide high reflectivity and were widely used. However, the spectral resolution of the multilayer, in order of a few percent, is poor compared with perfect crystals that provide a bandwidth of 10^{-4} or below. This limits the applications of multilayer in the cases of high spectral resolution. Therefore, several ways have been developed to narrow the reflectivity spectral width, including etching the multilayer into the lamellar grating, decreasing the thickness of the absorber layer and using high order reflectivity. In this article, the Mo/Si narrowband multilayer mirrors were designed for incidence angle of 5° at the wavelength of 14 nm using the combination of decreasing the thickness of Mo layer and utilizing high order reflectivity. Using a DC magnetron sputtering, these Mo/Si multilayer mirrors working in the 1^{st}, 2^{nd}, 3^{rd}, 4^{th} and 5^{th} order for the thickness of Mo layer of 2 nm and 3 nm have been fabricated, and then measured on National Synchrotron Radiation Facility in Hefei, China. The performances of these Mo/Si narrowband multilayer mirrors were shown in Fig. 1. As shown in Figs. 1(a) and (b), the spectral width both decreases with the increase of the reflectivity order. At the same reflectivity order, the spectral width is less for the thickness of Mo layer of t_{Mo}=2 nm than that for t_{Mo}=3 nm. The spectral width has been reduced to 0.12 nm in the 5^{th} order for t_{Mo}=2 nm, where the reflectivity is 18%.

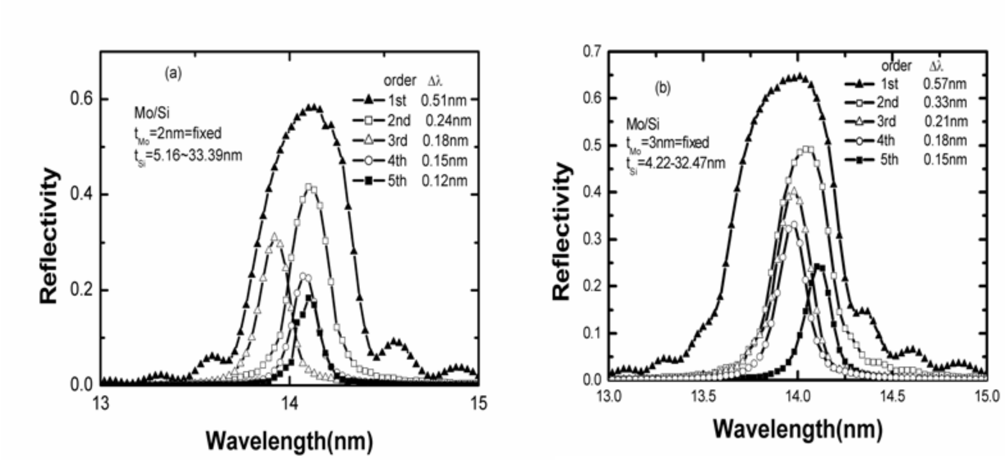

Fig. 1. *Measured optical performances of Mo/Si narrowband multilayers working in different reflectivity orders from 1^{st} to 5^{th} order, for the thickness of Mo layer of 2 nm (a) and 3 nm (b), respectively.*

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Investigation of X-ray multilayer structures using XRD in IPOE

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Abstract: X-ray diffractometer (XRD) is a powerful tool of structure analysis and has been used in laboratories. In this article, the investigation of X-ray multilayer structures using XRD in our lab was introduced. For the multilayer mirrors working in EUV and soft X-ray regions, the layer thickness is ultra-thin, in the order of nanometer, and the optical performances are affected sensitively by the deviation of the multilayer structures. Therefore, accurate determination of the parameters of multilayer structures is essentially important for the fabrication of the X-ray multilayer, including layer thickness, material ratio, interface roughness, material's density. These parameters can be obtained by fitting the measurement curves of X-ray diffraction without destroying the sample, not like TEM. Figure 1 shows the measured and fitting curves of W/B_4C multilayer with period thickness of 8 nm. By fitting the experimental data measured by XRD using the Evolutionary algorithms method, the structural parameters of this multilayer were determined, such as, W layer thickness 3.8 nm and B_4C layer thickness 2 nm, the interface roughnesses of each layer are 0.43 nm and 0.35 nm respectively. This is convenient to calibrate the fabrication process, because these measurement and fitting calculation are very easy and fast.

The interface roughness is the main influence factor of optical performances of multilayer, and should be reduced by modifying the fabrication technology. This requires determining the improvement of roughness. Using non-specular measurements, including offset scattering, rocking scan and detector scan, we can accurately distinguish the difference of interface roughness between different samples, even the difference as small as the order of 10^{-1} nm. Figure 2 shows the experiment curves of samples on different substrates. The substrate roughnesses of sample (A) and (B) are 0.3 nm and 0.5 nm respectively.

We also presented a method to measure the structure of low Z material layer using the X-ray reflectivity of single layer. For low Z material's optical constant is similar to the silicon substrate, the change of the low Z material layer thickness is difficult to determine. Our experimental results show that the carbon layer with thickness of 30 nm on silicon substrate can be measured.

All these methods are helpful to improve the fabrication technology of multilayers for X-ray optics.

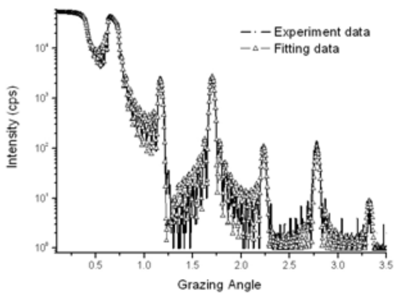

***Fig.** 1. Measured and fitting curves of W/B_4C multilayer*

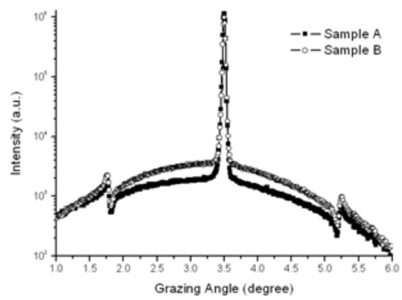

***Fig.** 2. comparison of two samples with different substrates roughness*

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Depth profiling of interdiffused layers in Fe/Si multilayers using standing-wave soft-X-ray fluorescence spectroscopy

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Fe/Si multilayers are widely studied from the aspect of the interlayer magnetic coupling. We have assigned the mediating layer for the interlayer coupling to be an amorphous $FeSi_2$ layer of 0.7 nm thick resulted from interdiffusion using soft-X-ray fluorescence (SXF) spectroscopy [1]. However, if the interdiffused layers have an asymmetric structure with respect to the Fe or Si layer, the SXF technique provides an average of the equivalent silicide layers on both sides. For further analysis of the interdiffusion layer the standing-wave technique is promising as in the X-ray region. Antinodes of the standing wave generated in the multilayer under the Bragg condition enhance the fluorescence locally, which can differentiate a silicide layer from the equivalent one on the opposite side.

An Fe(3.0nm)/Si(1.9nm)/Fe(3.0nm) trilayer deposited on a Mo(2.3nm)/B_4C(2.7nm) multilayer of 20 bilayers was prepared using a magnetron sputter system. Standing wave is generated dominantly by the Mo/B_4C multilayer, while it is slightly modulated by the trilayer. Standing wave was first confirmed to be present in the sample by measuring total photoelectron yield vs. incident photon energy. The SXF experiment was carried out at BL-16B using an SXF spectrometer of a flat-field focusing type under a resolution of about 0.4 eV at 100 eV.

Figure 1 shows the Si $L_{2,3}$ fluorescence spectra from the Fe/Si/Fe trilayer at 136.1 eV for 22° and 28° angles of incidence from the normal, where the latter angle was not under the Bragg condition. A slight difference is found between the two spectra in the shoulder region. Differences between 22° and 28° in the fluorescence intensity estimated by a curve fitting analysis for the silicide layers are summarized in Table I. The signs of $FeSi_2$ and Si are different, whereas those of Fe_3Si and Si are the same. It is not reasonable because the $FeSi_2$ layer is closer to the Si layer than the Fe_3Si layer. It must result from the symmetric layer model. From further studies it was found that the $FeSi_2$ layer above the Si layer is thinner than that below it, and vice versa for the Fe_3Si layer. Therefore, it is ascertained that the interdiffused layer has an asymmetric structure. The origin of the asymmetric structure is though still under question, our result means that the standing wave SXF technique is promising for interface analysis and thus depth profiling.

Reference
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Table I. Relative changes in the SXF intensity for the silicide layers between 22° and 28°.

Silicides	Fe_3Si	$FeSi_2$	a-Si	SiO_2
Change (%)	+13.5	-17.6	+9.4	-4.6

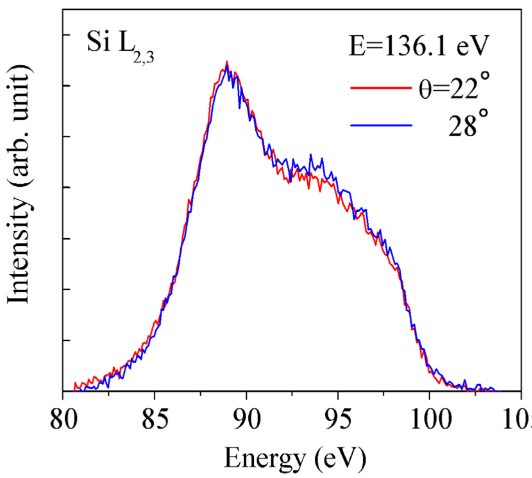

Fig. 1. Si $L_{2,3}$ SXF spectra from an Fe/Si/Fe trilayer for 22° and 28° angles of incidence at 136.1 eV.

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My Notes

	Sunday March, 12	Monday March, 13	Tuesday March, 14	Wednesday March, 15	Thursday March, 16	
08:00-08:30		**Opening remarks** **C. Schanzer**	**P. Jonnard**	**J. Maser**	**F. Delmotte** **J. Seely**	08:00-08:30
08:30-09:00		**K. Soyama**	**I. Kozhevnikov**	**I.A. Artyukov**	**C. Borel**	08:30-09:00
09:00-09:30			**T. Ejima** *Break*	**M.J. Pivovaroff**	**E. Gullikson** **A. Oehr**	09:00-09:30
09:30-10:00		**Th. Bigault** *Break*	**M.-F. Ravet**	*Break*	*Break*	09:30-10:00
10:00-10:30		**K. Hamamoto**	**Y. Ogasaka**	**R. Cuerno**	**S. Bajt**	10:00-10:30
10:30-11:00			**F. Eriksson** **Z. Wang**	**L. Peverini**	**E. Majkova**	10:30-11:00
11:00-11:30		**S. Yulin** **K. Murakami**		**A. Jensens**	**H.M. Hertz**	11:00-11:30
11:30-12:00		**I. Nedelcu**	**A.L. Aquila** **Z. Zhang**	**N. Ghafoor**	**Closing remarks**	11:30-12:00
12:00-12:30	**Registration**	**Free Time**	**Free Time**	**Free Time**		12:00-12:30
12:30-13:00						12:30-13:00
13:00-13:30						13:00-13:30
13:30-14:00						13:30-14:00
14:00-14:30						14:00-14:30
14:30-15:00						14:30-15:00
15:00-15:30						15:00-15:30
15:30-16:00						15:30-16:00
16:00-16:30						16:00-16:30
16:30-17:00						16:30-17:00
17:00-17:30						17:00-17:30
17:30-18:00						17:30-18:00
18:00-18:30		**Dinner**	**Dinner**	**Dinner**		18:00-18:30
18:30-19:00						18:30-19:00
19:00-19:30	**Welcome Reception** **Buffet Dinner**					19:00-19:30
19:30-20:00						19:30-20:00
20:00-20:30		**POSTER SESSION 1**		**POSTER SESSION 2**		20:00-20:30
20:30-21:00						20:30-21:00
21:00-21:30						21:00-21:30
21:30-22:00						21:30-22:00