The International Conference on Physics of X-Ray and Neutron Multilayer Structures (PXRNMS) 2023

11-13 October 2023, Himeji Convention Center, Himeji, Hyogo, Japan

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Welcome address

On behalf of the Center for EUVL, Laboratory of Advanced Science and Technology for Industry, University of Hyogo, and Optical Design Laboratory, Tokyo Polytechnic University, we invite you to attend the International Conference on Physics of X-Ray and Neutron Multilayer Structures (PXRNMS) 2023. This conference follows the fruitful PXRNMS 2018 organized by the colleagues of the Laboratoire Charles Fabry, Institut d'Optique Graduate School and the Laboratoire de Chimie Physique - Matiere et Rayonnement, Sorbonne Universite and CNRS, as well as the former PXRMS conferences that were successfully organized for many years.

This is an international conference, with approximately 80 participants each year, with approximately half of the participants coming from Europe and America. It is held every two years mostly in the United States, Europe, and Japan. The conference will then focus on the physics of nanometer-scale multilayer films optimized for various applications such as extreme ultraviolet (EUV) and X-ray regions, as well as neutrons and ion beams, and the main topics discussed are listed as follows. This time, 26 oral and 16 poster presentations will be presented. and it will be expected approximately 90 attendees.

- Multilayer Design and Modeling
- Film Growth and Microstructure
- Roughness and Interface Formation
- Surface and Thin-Film Modifications using Ion Beams
- Film Removal Techniques
- Growth Models and Computer Simulations
- X-Ray and Neutron Scattering
- Surface and Interface Topography
- Layer and Interface Composition
- Wavefront Characterization and Correction
- Mechanical Properties and Stability
- Optical Properties
- Novel Characterization Techniques
- Polarization Control
- Metrology

The technological development of optical elements such as multilayer mirrors, which are necessary for the application of quantum beams to measurement technology, is essential for the future development of science and technology. In fact, Mo/Si multilayer film technology is an essential technology for EUV lithography, and due to the success of this technology, it has been applied to the manufacturing technology of semiconductor logic devices of 7 nm and above since 2019. I sincerely hope that technologies from this conference will be realized in the near future. The academic research that contributes to basic science and industrially applied technology will be born through this conference, ranging from basic research to applied technology and practical application.

All the program committee members and organizers and are very happy to hold this conference face-to-face under the COVID-19 control, and we look forward to many useful discussions at this conference.

Yours sincerely,

Takeo Watanabe

Takeo Watanabe

Chief organizer of PXRNMS2023 in Japan

Professor,
Center for EUVL, Director,
Laboratory of Advanced Science and Technology for Industry, Special Assistant to the Director,
Special Assistant to the President,
University of Hyogo, Japan

Organizers

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- **Dr. Tetsuo Harada**, Center for EUVL, University of Hyogo, Japan
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- **Prof. Takeo Watanabe**, Center for EUVL, University of Hyogo, Japan

PXRNMS2023 Program

Oral Presentation
Wednesday, 11th Oct. Page No.

Conference Place: Medium Hall of Acrea Himeji

https://www.himeji-ccc.jp/img/pdf/pamphlet_A4-en-202304.pdf

9:00 **Coffee & Sandwitch**

9:55 **Opening Remarks**

Takeo Watanabe (Univ. of Hyogo)

(Keynote)
10:05 Development and Application of Multilayer Mirror 13

Hisataka Takenaka (TOYAMA)

(Invited)
10:45 Tailoring the nanoscale multilayer optics with high efficiency and precision for EUV, X-ray and Neutron applications 14

Qiushi Huang, Runze Qi, Zhe Zhang, Zhong Zhang ,
Wenbin Li, Shengzhen Yi, Zhanshan Wang (Tongji University)
Igor V. Kozhevnikov (Shubnikov Institute of Crystallography))

11:10 **— Coffee Break (30 min)—**

(Invited)
11:40 Interface characterization of neutron and X-ray multilayer using Grazing Incidence X-ray Absorption & Fluorescence spectroscopy experiments at Indus-2 SRS 15

Arup Biswas (Bhabha Atomic Research Centre)

(Invited)
12:05 Current Status and Prospcet for EUV Lithograpy Which Is a Significant Application Using Multilayers 16

Takeo Watanabe, Tetsuo Harada, and SHinji Yamakawa (Univ. of Hyogo)

12:30 **— Lunch (90 min) with Lunch box @ 409 meeting room —**

(Invited)
14:00 Resolving and improving the interfaces of Soft X-ray Multilayers 17

Marcelo Ackermann (Univ. of Twente)

14:25 High Reflective C/B Multilayer for Beyond EUV Lithography 18

Tetsuo Harada, Umi Fujimoto, Shinji Yamakawa, Takeo Watanabe (Univ. of Hyogo)

14:45 **— Coffee Break (30 min)—**

15:15 **Poster Presentations (120 min) @ Foyer of Medium Hall**

17:15 **Communication Party @ Foyer of Medium Hall**

Oral Presentation
Thurthday, 12th Oct.

8:30	**<u>Coffee & Sandwitch</u>**	
9:00	**(Invited)** Multilayer reflective optics for intense high-energy X-rays at SPring-8 <u>Takahisa Koyama</u> (Japan Synchrotron Radiation Research Institute (JASRI))	19
9:25	Highly efficient ultra-low blaze angle multilayer grating <u>Dmitriy Voronov</u>, Sooyeon Park, Eric Gullikson, Farhad Salmassi and Howard Padmore (Lawrence Berkeley National Laboratory)	20
9:45	Multilayer-coated blazed grating for high transmission tender X-ray energy range monochromator <u>Andrey Sokolov</u>, Stephanie Lemke, Svyatoslav Alimov, Jeniffa Knedel, Oliver Kutz, Tino Seliger, Grzegorz Gwalt, Franz Schfers, Friedmar Senf, Frank Siewert, Jens Viefhaus (Helmholtz-Zentrum Berlin fr Materialien und Energie, BESSY-II, Berlin, Germany) Qiushi Huang, Yeqi Zhuang, Runze Qi, Zhong Zhang, Wenbin Li, Zhanshan Wang (Key Laboratory of Advanced Micro-Structured Materials MOE, Institute of Precision Optical Engineering, School of Physics Science and Engineering, Tongji University, Shanghai, China)	21
10:05	**— Coffee Break (30 min)—**	
10:35	Optimisation of Cr/Sc-based multilayer coatings for water window applications <u>Evgueni Meltchakov</u>, Sbastien de Rossi, Eirini Papagiannouli, Franck Delmotte (Universit Paris-Saclay, Institut d'Optique Graduate School) Blandine Capitanio, Pascal Mercere (Synchrotron Soleil)	22
10:55	Synthesis and characterization of short- and ultrashort W-based multilayers for soft x-rays <u>Dennis IJpes</u>, Andrey E. Yakshin, Jacobus M. Sturm, Marcelo D. Ackermann (University of Twente)	23
11:15	NiV-based Multilayer for Soft and Hard X-ray Mirrors <u>Zhe Zhang</u>, Qiushi Huang, Runze Qi, Zhong Zhang, Zhanshan Wang (Key Laboratory of Advanced Micro-Structured Materials MOE, Institute of Precision Optical Engineering, School of Physics Science and Engineering, Tongji University, Shanghai, P. R. China)	24
11:35	**— Lunch with Lunch box @ 409 meeting room —**	
13:00	**Bus DEPARTURE time @ Acrea Himeji** **To Excursion** of SPring-8, SACLA, NewSUBARU synchrotron facility	
17:00	**Bus Arrival time @ Himeji Station** Himeji Station South Charter Bus Boarding Area <u>https://goo.gl/maps/PYdjtS6vETic68cQ6</u>	
18:00	**Bus DEPARTURE time @ Himeji Station** **To Banquet** at NADA-GIKU Japanese Sake Traditional Restaurant	
19:00	**Banquet 120 min**	
21:30	**Bus Arrival time @ Himeji Station**	

Oral Presentation
Friday, 13th Oct.

8:30 **Coffee & Sandwich**

(Invited)
9:00 Wide Bandwidth Neutron-Spin Polarizer Due to Ferromagnetic Interlayer Exchange Coupling — 25

Ryuji Maruyama (Japan Atomic Energy Agency (JAEA))

(Invited)
9:25 11B4C-containing Ni/Ti multilayer neutron optics — 26

Fredrik Eriksson, Sjoerd Stendahl, Naureen Ghafoor, Anton Zubayer, and Jens Birch (Linkping University, Sweden)
Mattias Schwartzkopf (DESY, Hamburg, Germany)

9:50 Material design optimization for large-m 11B4C-based Ni/Ti supermirror neutron optics — 27

Naureen Ghafoor, Sjoerd Stendahl, Anton Zubayer, Marcus Lorentzon, *Alexei Vorobiev, Jens Birch, Fredrik Eriksson
(Department of Physics, Chemistry, and Biology, IFM, Linkping University, Sweden, *Department of Physics and Astronomy, Material Physics, Uppsala University, Sweden, and Institut Max von LauePaul Langevin (ILL), Grenoble, France)

10:10 10B/11B-modulated chemically homogeneous boron carbide neutron interference mirrors — 28

Jens Birch, Sjoerd Stendahl, Samira Dorri, Anton Zubayer, Naureen Ghafoor, Fredrik Eriksson (Linkping University)

10:30 **— Coffee Break (30 min)—**

(Invited)
11:00 All-dielectric multilayer mirrors tuned at vacuum ultraviolet wavelengths — 29

Paloma López-Reyes, Nuria Gutirrez-Luna, Carlos Honrado-Bentez, and Juan Ignacio Larruquert (GOLD-IO-CSIC Instituto de ptica Consejo Superior de Investigaciones Cientficas, Serrano 144, 28006 Madrid, Spain)

11:25 Design Study of Soft X-Ray Aplanat with Four Multilayer Mirrors in Grazing Incidence Configuration — 30

S. Yamashita, M. Toyoda (Tokyo Polytechnic University)

11:45 Thermally stable MoNx/Si1-xNx multilayer as a substrate for XSW study of SMSI — 31

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(Industrial Focus Group XUV Optics, MESA+ Institute for Nanotechnology, University of Twente, Enschede, Netherlands)

12:05 Surface roughening by ion beams: Is ballistics “be-all and end-all”? — 32

Parikshit Phadke, Jacobus M. Sturm, Fred Bijkerk, Marcelo D. Ackermann (University of Twente)

12:25 **— Lunch (90 min) with Lunch box @ 409 meeting room —**

(Invited)
13:55 More accurate prediction of optical constants: A prerequisite for the development of next-generation metrology instruments based on soft X-rays — 33

Victor Soltwisch (PTB)

14:20 Bayesian Inferences and Time-Frequency Analysis Assisted Determination of Optical Constants in the EUV 34

Qais Saadeh, Victor Soltwisch, Christian Laubis, Michael Kolbe, and Frank Scholze (PTB)

14:40 Refractive index measurements with improved accuracy for EUV/x-ray multilayer optics 35

Franck Delmotte, Eirini Papagiannouli (Universit Paris-Saclay)
Regina Soufli, Catherine Burcklen (Lawrence Livermore National Laboratory)
Farhad Salmassi, Eric Gullikson (Lawrence Berkeley National Laboratory)

15:00 **Closeing Remarks**

Poster Program

Wednesday, 11th Oct. 15:15 - 17:15

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The poster board will be availavle from the morning of 11th to the end of th conference. The board size is W1200 mm x H1800 mm. (Recommended poster format: A0 Portrait)

1 Enhancement of Diffraction Efficiency and Spectral Flux with Quasi-Graded Index Coating (QGIC) on Soft X-Ray Laminar-Type Diffraction Gratings Optimized for B-K and Li-K Emissions — 39

Masato Koike1-3, Tadashi Hatano2, Alexander S. Pirozhkov1, Masami Terauchi2
(1 Kansai Photon Science Institute, Fundamental Quantum Sciences Directorate, National Institutes for Quantum Science and Technology
2 Institute of Multidisciplinary Research for Advanced Materials, Tohoku University
3 Laboratory of Advanced Science and Technology for Industry, University of Hyogo)

2 Development of Narrowband Multilayer Mirrors for Extracting a Single Harmonic from an EUV HHG Source — 40

Suet Yi Liu, Yuya Iwamoto, Hisataka Takenaka (TOYAMA Co. Ltd, Japan)
Hiroki Mashiko, Satoshi Ichimaru, Masatoshi Hatayama (NTT Advanced Technology Corporation, Japan)
Eric Gullikson (Center for X-ray Optics, Lawrence Berkeley National Laboratory, USA)
Tomoya Mizuno, Takayuki Kurihara, Jiro Itatani (Institute for Solid State Physics, the University of Tokyo, Japan)

3 Resolving buried interfaces by Low-Energy Ion Scattering — 41

Adele Valpreda, Jacobus M. Sturm, Andrey E. Yakshin, Marcelo Ackermann (University of Twente)

4 Fabrication and characterization of EUV multilayer gratings — 42

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B. Capitanio, M. Thomasset (Synchrotron SOLEIL)

5 EMIL@BESSY-II: In-situ investigations of material combinations at a synchrotron light source — 43

Stefan Hendel, Regan G. Wilks, Mihaela Gorgoi, Anna Efimenko, Marcus Br (Helmholtz-Zentrum Berlin)

6 Upgrades of PTB’s EUV Reflectometry Instrumentation — 44

Andreas Fischer, Christian Laubis, Michael Kolbe, Frank Scholze ((PTB) Physikalisch-Technische Bundesanstalt)

7 Optical Constants of Carbon and Boron material for Beyond EUV Lithography — 45

Umi Fujimoto, Tetsuo Harada, Shinji Yamakawa, Takeo Watanabe (Univ. of hyogo)

Oral Session

Development and Application of Multilayer Mirror

Hisataka Takenaka

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In the 1971, the development of multilayer mirrors started to progress after E. Spiller demonstrated through calculations that soft X-ray practical normal incidence reflectivity could be achieved with multilayer mirrors. In the late 1970s, United States researchers, T. W. Barbee, Jr., and J. H. Underwood, began fabricating multilayer mirrors, such as W/C and V/C, using Magnetron sputtering. At the same time, Europe, and Russia also developed multilayers. In 1981, A. E. Rosenbulth showed through calculations that Mo/Si multilayer mirrors exhibited high reflectivity near a wavelength of 13 nm. This led to the advancement of Mo/Si multilayer mirror fabrication, the development of X-ray telescopes, and X-ray microscopes using Mo/Si multilayer coatings. In 1985, T.W. Barbee and Jr. achieved a 60% reflectivity at a wavelength of 17nm and an incident angle of 20 degrees with Mo/Si films. Additionally, in 1987, A.B.C. Walker and Barbee's group created an X-ray telescope utilizing Mo/Si multilayer mirrors for observing the solar corona. These developments marked an active period of multilayer mirror advancement from the late 1970s to the 1980s.

In Japan, multilayer mirror development has been underway since the early 1980s at institutes such as Tohoku University, NTT, Canon, Nikon. Initially, W/C multilayer mirrors were fabricated using Ion beam sputtering at Tohoku University and NTT. In NTT, Magnetron sputtering was also used to fabricate W/C multilayer mirrors and developed a spectrometer by combining a diffraction grating and these W/C mirrors. During that time, H. Kinoshita applied multilayer mirrors for what is now known as EUVL (Extreme Ultraviolet Lithography, formerly called Soft-Xray Projection Lithography) and developed an early-stage optical system for EUVL, initially using W/C multilayer mirrors. Later on, Mo/Si multilayer mirrors with high reflectivity near a wavelength of 13 nm were employed as the EUVL multilayer mirrors. Since then, Mo/Si multilayer mirrors have remained effective in EUV applications, leading to various applications. In this presentation, the development of Mo/Si multilayer mirrors and their applications mainly in Japan will be introduced.

Tailoring the nanoscale multilayer optics with high efficiency and precision for EUV, X-ray and Neutron applications

Qiushi Huang[1*], Runze Qi[1], Zhe Zhang[1], Zhong Zhang[1], I. V. Kozhevnikov[2], Wenbin Li[1], Shengzhen Yi[1], Zhanshan Wang[1**]

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Multilayer (ML) optics is one of the enabling technology in EUV, X-ray and Neutron applications, based on its advantage of high efficiency beyond the total external reflection regime. Institute of Precision Optical Engineering (IPOE) in China started working in this field from 2001, and gradually building up the capacity to develop ML coatings, ML nanostructures, and ML-based optical systems. Our recent work in these areas will be presented. Hard X-ray multilayer monochromators can bring one to two orders magnitude higher flux than crystal monochromators and are widely needed in synchrotron radiation facility. Pd/B_4C multilayer with d-spacing of 2.5nm was developed using magnetron sputtering with both Ar and Kr gas and the former one shows slightly better layer structure. Its stability was further tested under liquid nitrogen cooling and different humidity environment. Combined with the deterministic surface figuring technique and metrology, high precision multilayer mirrors with maximum 350mm length were manufactured with 30pm d-spacing error (PV), and 1.5 nm (RMS) figure error. These mirrors have been installed in the double ML monochromator in Shanghai synchrotron radiation facility. Sc/Si multilayer is an optimum structure for working around 46.5nm. The microstructure and mechanical stability of the thick Sc/Si multilayer were studied and improved via doping sublayers during deposition. Ni/Ti ML supermirrors with M=3 has also been developed for neutron beamline application. The multilayer was further combined with nanostructures forming high efficiency X-ray diffraction optics, like the ML gratings. In collaboration with the BESSY-II optics group, a first Cr/C multilayer blazed grating has been installed in the monochromator of TXM beamline in BESSY-II, providing two orders of magnitude enhancement of photon flux at 2keV. To achieve both high efficiency and high resolution, multilayer gratings using higher line density and higher diffraction orders are being studied. Based on the above-mentioned ML technology, EUV and X-ray optical systems are being developed. A lab-based EUV radiation damage system working at 13.5nm has been built using laser plasma source and Mo/Si coated Schwarzschild system. Last year, the Solar Upper Transition Region Imager (SUTRI) using Sc/Si ML based imaging system was successfully launched and has obtained the first 46.5nm image of the sun in China.

Interface characterization of neutron and X-ray multilayer using Grazing Incidence X-ray Absorption & Fluorescence spectroscopy experiments at Indus-2 SRS

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X-rays reflecting from each interface of a multilayer interfere with the incident wave and a standing wave is created inside the multilayer structure. Using synchrotron X-ray local structures at the interfaces and depth resolved element specific interface diffusion can be studied by Grazing Incidence Extended X-ray Absorption Fine structure (GIEXAFS) and Grazing Incidence X-ray Fluorescence (GIXRF) measurements respectively. Along with interface roughness these interfaces properties of multilayer thin film are very critical in application of neutron and X-ray optics. In our laboratory using magnetron and ion beam sputtering techniques it has been demonstrated [1-6] that the reflectivity of neutron supermirror and soft x-ray multilayer mirror can be improved either by introducing Air or N_2 gas along with Ar gas into the plasma or by introducing a very thin barrier layer of C or B_4C at the interface of the two materials. Various structural and spectroscopic investigation of the interface of multilayer have been done. In this presentation results of GI-EXAFS and GIXRF measurements done with Indus-2 SRS on Ni/Ti [1-3], Mo/Si [4], Cr/Ti [5] & Cr/Sc [6] will be presented along with specular and non-specular GIXR results. Recrystallization of NiTi at the interfaces has been observed at higher temperature annealed sample and it has been found that the amorphous Ni/Ti multilayer is more preferable for recrystallization. This finding has been supported by molecular dynamics (MD) simulation of Ni/Ti multilayer. Along with this the effect of C and B_4C diffusion barrier on the interface of Mo/Si EUV multilayer and Cr/Ti & Cr/Sc water-window soft x-ray multilayer will be discussed.

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6. Piyali Sarkar, Arup Biswas, Ravi Kumar, Sanjay Rai, S Jha, Dibyendu Bhattacharyya, Physical Chemistry Chemical Physics 25 (2023) 3072

Current status and prospect for EUV lithography which is the significant application using multilayers

Takeo Watanabe[1], Tetsuo Harada[1], and Shinji Yamakawa[1]

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EUV (extreme ultraviolet) lithography started to use in high volume manufacturing (HVM) of 7-nm+ node logic devices from 2019. According to the International Roadmap for Devices and Systems [1], EUV lithography will be used for the HVM of 0.5-nm node logic devices.

Currently, the multilayers and exposure wavelength on EUV lithography is molybdenum/silicon (Mo/Si) and 13.5 nm, respectively. Mo/Si multilayer mirrors for EUV at the wavelength of 17 nm was presented by the research group of Stanford University and University of California in 1985 [2]. The contribution of R&D of Mo/Si was done by the research group at NTT in Japan [3]. The research group of NTT Atsugi R&D Center demonstrated the X-ray projection lithography and they presented at the 47th Japan Society of Applied Physics Autumn Meeting in 1986 [4]. They used W/C multilayers on Schwarzschild optics for the imaging optics. The stencil mask was used to replicate 0.2 mm width resist pattern by Polymethyl methacrylate (PMMA) employed as a resist material. And the research group of NT&T and AT&T demonstrated the X-ray projection lithography using Mo/Si Schwarzschild optics in 1989 [5] and in 1990 [6], respectively. However, since the exposed area size was too small to fabricate the semiconductor LSI devices, the Offner-type of ring-field optics was introduced to enlarge the exposure area for the practical use [7]. Using this optics, NTT research group demonstrate 150 nm resist pattern by two aspherical imaging optics in 1991 [8]. Three aspherical imaging optics was design independently by the research group at University of Hyogo [9] and EUV LLC [10], USA. To increase the exposure area size on a wafer, the mask and wafer synchronized stage control system was employed. The research group at University of Hyogo demonstrated 60 nm L/S resist pattern on a wafer with an large exposure area size of 10×10 mm^2 [11]. And furthermore, many research groups has been contributed on EUV lithographic technology to pull up to the fabrication level of the semiconductor devices. Currently, ASML products the exposure tool which employes the six aspherical imaging optics which has the numerical aperture of 0.33 and synchronized control of mask and wafer stages to exposure ULSI pattern.

The technical issues on EUV lithography are 1) EUV resists development of the simultaneous achievement of high resolution, high sensitivity, and low line with roughness (LWR), 2) defect free mask and its metrology and repair, and EUV pellicle which has high transmittance and long lifetime on EUV exposure, and 3) high power and high stability of EUV light source. In the presentation the current status will be introduced. And the future prospect for EUV high and hyper NA, and the shortening the wavelength of EUV will also be introduced and discussed [12].

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Resolving and improving the interfaces of Soft X-ray Multilayers

Nanometer-level d-spacing multilayers are key optical elements with applications from advanced lithography to X-ray optical elements for X-ray fluorescence and astronomical instruments. In all these applications, the quality of the thin films, but most importantly the sharpness of the interface between the layers is key to achieving high reflectivity. Roughness, intermixing and compound formation at these interfaces result in reflectivity losses.
In order to improve these interfaces, metrology is needed to resolve on the atomic level, what the driving mechanisms are that lead to reflectivity loss. At the sub-nm scale, a single technique is often insufficient to fully understand the physics of intermixing: Whereas TEM and XRR can resolve the local atomic or electronic density, XPS is optimal to highlight compound formation. We demonstrate that only a combination these techniques can truly resolve the interface. In addition, we have developed a novel capability to resolve buried interfaces with LEIS – using a full modelling of the LEIS signal outside the surface peaks – offering atomic density resolution rather than electronic.
For 2.5nm and 1 nm W/Si multilayers, this combination of techniques shows that the interaction between W and Si results in WSi_x formation, leading to poor optical performance. The introduction of ultrathin 0.1 nm B_4C diffusion barriers shows clear improvement in reflectivity, and through the combination of these multiple surface-sensitive techniques we can directly explain how the barriers contribute to a higher reflectivity.

Bio

Marcelo Ackermann is chair of the Industry Focus Group – X-ray and EUV (XUV) optics at the MESA+ institute of the University of Twente. He obtained his PhD in physics (cum laude) in 2007 on a shared research project between Leiden University and the ESRF in Grenoble, under the guidance of Prof Frenken and Prof. Ferrer. After that he held different leading positions in industrial research for the development of X-ray, visible and IR optics at cosine Research, Helbling Technik, SCHOTT Advanced Optics and ASML. In 2020 he re-joined academia as full professor in the XUV group, focussing on the development of next generation reflective, refractive and transparent X-ray and EUV optics in collaboration with industrial partners like Zeiss, ASML and Malvern Panalytical.

High Reflective C/B Multilayer for Beyond EUV Lithography

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Beyond EUV (BEUV) lithography technology with exposure wavelength around 6.7 nm is expected as next generation lithography. The development of multilayer with high reflectivity is a critical issue for BEUV lithography.

Many La/B-based multilayers were reported as a high theoretical reflective multilayer.[1] However, the temporal stability of La/B-based multilayers is low because of the high reactivity of La. Thus, we propose carbon/boron (C/B) multilayer as a new BEUV multilayer. The C/B multilayer has high theoretical reflectance of about 80%, which is comparable to La/B multilayer shown in Fig. 1(Left). The optical constant of the C film depends on its density, and high density is required to obtain high reflectance and wide reflection bandwidth. The calculated reflectance of the multilayer with varied carbon densities is shown Fig. 1(Right). The higher density carbon is needed for the high reflectance and wide bandwidth. In the Fig. 1(Left), high density carbon with 3.1 g/cm^3 is used for the calculation, which is highest value for the diamond like carbon (DLC) film. We will discuss the performance of the C/B multilayer.

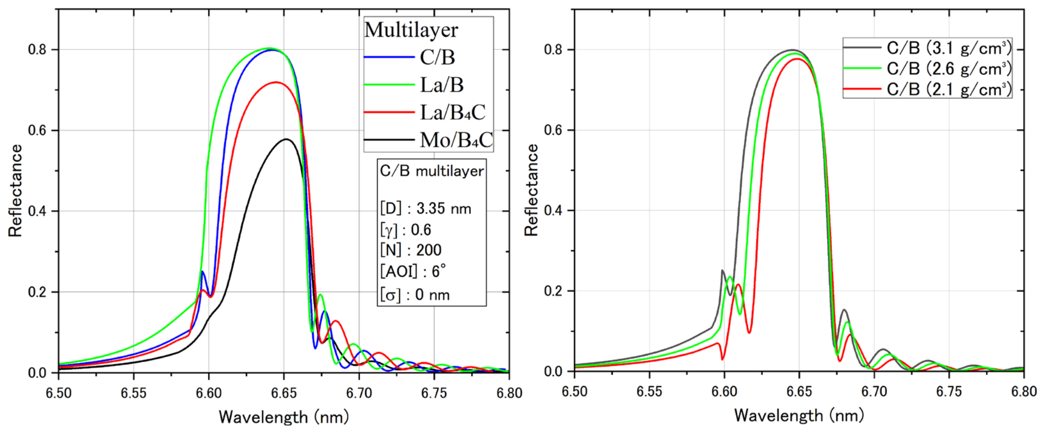

Figure 1. Calculated reflectance of C/B multilayers. (Left) Comparison of La, Mo, and C materials. (Right) Carbon density dependence of the multilayer reflectance.

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Multilayer reflective optics for intense high-energy X-rays at SPring-8

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A high-energy X-ray beam is a powerful probe for non-destructive analysis of large sized objects, thick heavy metals, devices enclosed with exterior cases, and materials in a high-pressure cell. One of the key characteristics of SPring-8 is to provide highly brilliant X-rays in high-energy region. Usually, high-energy X-rays are generated by a double crystal monochromator (DCM) with an energy bandwidth of less than 0.01%, which is too narrow for applications such as transmission X-ray imaging, orientation imaging, and total-scattering measurement. By using a double multilayer monochromator (DMM) consisting of two multilayer mirrors with an energy bandwidth of 1-5%, the photon flux can be dramatically increased compared with that of DCM. Recently, we designed and installed DMMs at SPring-8 in two beamlines, BL20B2 and BL05XU, for applications using intense high-energy X-rays.

At SPring-8 BL20B2 (bending magnet beamline for large field of view imaging), we designed and installed two pairs of W/B_4C multilayer mirrors as DMMs to enhance flux density of 40 keV and 110 keV [1]. At an experimental hutch located 210 m away from the source, a large and uniform beam of size 14 mm (V) × 300 mm (H) was generated with a high flux density at 110 keV, which marked a 300 times increase in the photon flux when compared with a DCM with Si 511 diffraction.

At SPring-8 BL05XU (undulator beamline for test bench of developing next generation beamline optics) [2], we designed and installed a DMM, multilayer focusing mirrors (MFMs), and a multilayer reflective beam expander (MRBE). In this beamline, these multilayers were deposited at the SPring-8 in-house laboratory. 100 keV X-rays with 1% bandwidth were generated by using the DMM consisting of a pair of Cr/C multilayer mirrors. By combining the DMM with the MFMs that consist of W/C laterally graded multilayer mirrors in a Kirkpatrick-Baez geometry, the focusing beam size of 0.3 μm with a high flux of 6×10^{10} ph/s at 100 keV was achieved. Additionally, by combining the DMM with the MRBE that consists of a W/C laterally graded multilayer on a hyperbolic shape mirror, a field of view of 5 mm square can be available for high-speed imaging of metallic bulky samples.

In this presentation, I will describe these results of the developments.

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Highly efficient ultra-low blaze angle multilayer grating

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A multilayer blazed grating can be used as a highly efficient spectral purity filter for EUV lithography. Angular separation of the light of wavelength of 13.5 nm from infrared and out-of-band deep ultraviolet radiation is provided by diffraction into 1st diffraction order. To avoid excessive dispersion of EUV radiation over the exit aperture the grating should have a large period of 5 - 10 μm. At the same time the grating groove depth should be very small to match the multilayer d-spacing, leading to extremely low blaze angles of 0.1° or so. Fabrication of such low aspect ratio structures is hardly possible with existing grating fabrication techniques. We developed a process of reduction of a groove depth of a coarse blazed grating with a blaze angle of few degrees down to a nanometer scale, achieving the ultra-low blaze angles. The coarse Si grating is planarized by a polymer material and then etched with a plasma which provides etching of planarization layer and underlying Si grating with slightly different etch rates. The approach provides a way to adjust the blaze angle to any lower value with high accuracy. We demonstrate the reduction of the blaze angle to an extremely low value of 0.04°±0.004°. For a 100 lines/mm grating with a Mo/Si multilayer coating, the grating exhibits diffraction efficiency of 58% in the 1st diffraction order at a wavelength of 13.3 nm.

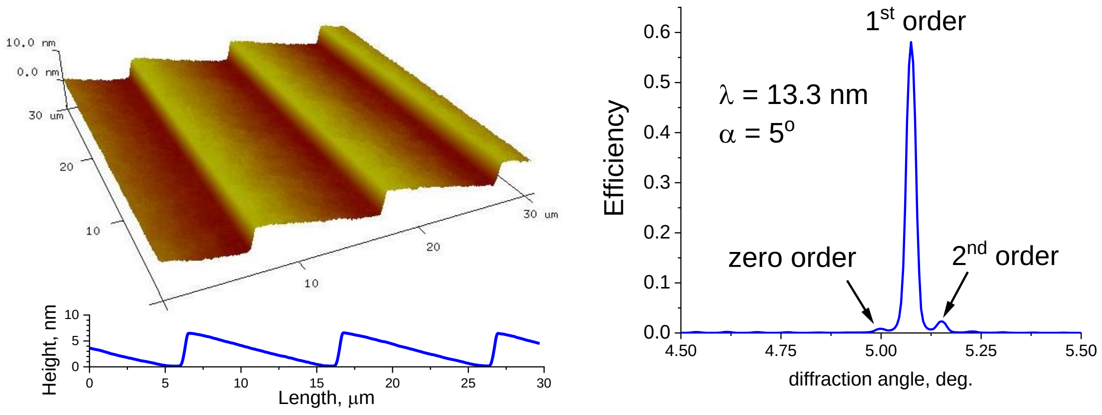

Figure 1. AFM image, groove profile and efficiency measurements of 100 lines/mm blazed grating coated with a Mo/Si multilayer.

Multilayer-coated blazed grating for high transmission tender X-ray energy range monochromator

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Multilayer coating on top of high line density blazed gratings can increase its diffraction efficiency up to one order of magnitude for a selected diffraction order. In combination with multilayer coated pre-mirror in plane grating monochromator (PGM) the total instrument transmission can be increased in hundreds of times. In our developments on multilayer-coated blazed gratings (MLBG) we have reached experimentally efficiency up to 60% [1,2] in tender energy range where single coated grating would demonstrate only few percent. The key factor of high performance MLBG is in correct optimization of both multilayer and grating profile parameters to each other [3]. After several successful prototypes the real MLBG were designed and installed in c-PGM at u41-TXM-beamline at BESSY-II [4].

In our contribution we present recent research on MLBGs with extended energy region up to 8.5keV. Experimentally measured efficiency on our first prototype high line density Ni/B4C ML coated grating demonstrated extraordinarily high value of 60% at 7keV. One of the main challenges for application MLBGs in PGM together with ML coated pre-mirror is caused by asymmetric beam propagation in multilayer on grating with slightly different path relative to plane mirror case. Thus, to fulfill PGM geometry the optimal ML period thicknesses for mirror and grating should be slightly desynchronized. This effect becomes stronger with higher energy. Several possible solutions for ML coated optics PGM are suitable as for undulator as well for dipole based beamlines will be presented and compared.

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Optimisation of Cr/Sc-based multilayer coatings for water window applications

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Development of efficient normal incidence optics for the soft x-ray range and, in particular for the water window (a region between absorption edges of carbon and oxygen, from 282 to 533 eV) remains quite a challenge. Proposed more than 20 years ago, a most promising system, the Cr/Sc multilayer, provides theoretical reflectivity about 60% at near-normal incidence around the Sc $L_{2,3}$ edge at 397 eV. However, the measured peak reflectance of Cr/Sc multilayers achieved so far is much lower (around 20% in the previous publications) because of a number of reasons. Apart of the problem of stability while depositing several hundreds of sub-nanometer layers, the most significant reflectivity loss is caused by formation of a rough interfaces as a result of the material interdiffusion and/or thin film growth process.

At the last PXRNMS conference in 2018 we reported on our approach to design high-reflectance Cr/Sc-based multilayer mirrors using a process of nitridation of chromium during deposition and adding boron carbide (B_4C) as a third material in the periodic structure. We have already demonstrated that with this type of coating a peak reflectance exceeds 20% in the vicinity of the Sc L-edge at near-normal incidence [1].

Since that time we have elaborated our method and produced several series of CrN/B_4C/Sc multilayer mirrors deposited by magnetron sputtering. The multilayers have been characterized by grazing incidence x-ray reflectometry and at-wavelength measurements. The normal incidence reflectivity with a peak reflectance higher than 30% was measured at the Metrology beamline of Soleil synchrotron. We will present and discuss the main results of the study and problems that we have encountered. In fact, an accurate calculation of the CrN/B4C/Sc multilayer reflectivity is hardly possible due to a lack of reliable optical constants of CrN in general and in this spectral range in particular. So we had to use an experimental approach in order to find an optimal thickness ratio of materials in the multilayer structure which provides a maximum reflectance gain. It was determined with a series of multilayers of relatively small period number (N=50). Based on this finding, we have proceeded with 500-periods samples, the number closed to that corresponding to saturated values of the peak reflectance for this system.

This study was able to confirm our strategy of optimisation for this new multilayer system which proved to be potentially interesting for various water window applications such as, for instance, x-ray microscopy.

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Synthesis and characterization of short- and ultrashort W-based multilayers for soft X-rays

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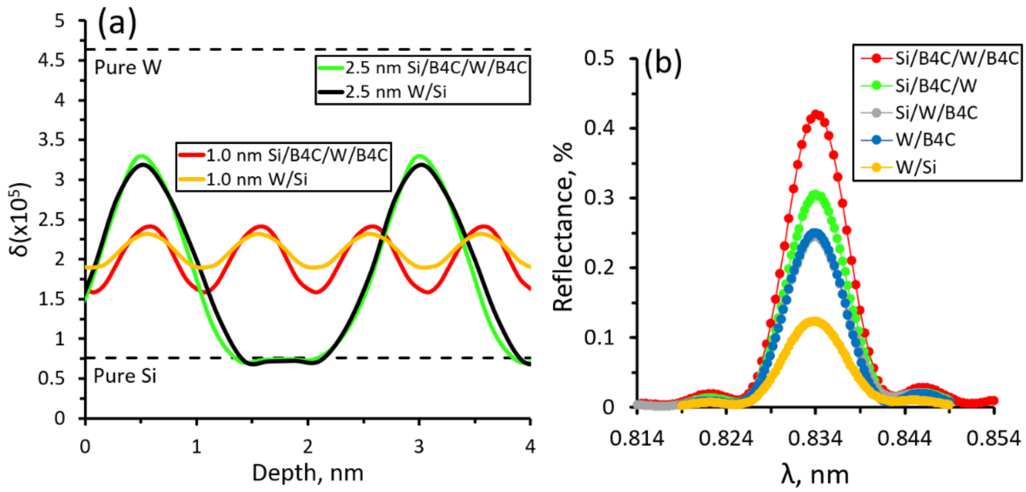
Short- and ultra-short period multilayer (ML) structures play a crucial role in applications such as synchrotron-based research, X-ray microscopy in the water window region, soft and hard X-ray astronomy and in wavelength dispersive X-ray fluorescence (WD-XRF). In WD-XRF a ML serves as an analyzing crystal to resolve emission lines of light elements in the O-Kα – Al-Kα range (λ=2.36 – 0.834 nm). The key requirement for the ML is to be highly reflective in the entire emission range, while also providing sufficient angular dispersion to resolve specific XRF lines. For these reasons, MLs with periods ranging from 1.0 to 2.5 nm are of great interest in this field. Due to the short period, the reflectance of such MLs is extremely sensitive to interface imperfections such as roughness and interdiffusion. Furthermore, the individual layers are only several angstroms thick, approaching the limit of materials to grow a continuous and closed film.

Our research focuses on synthesis and characterization of MLs with 2.5 nm and 1.0 nm periods, combining tungsten (W) absorber with B_4C, Si and Al spacers. These combinations show high theoretical reflectance in the O-Kα – Al-Kα range. However, formation of optically unfavourable compounds, high intermixing and interface roughness results in limited reflectance. In our work we used a variety of techniques including diffusion barriers, seed layers and ion polishing in sputter-deposited MLs in order to address these issues. Using the approaches described in our work, we successfully reduced compound formation, intermixing and interface roughness – resulting in a substantial increase in soft X-ray reflectance for W/Si, W/B_4C and W/Al MLs.



(a) Delta profiles of 2.5 nm and 1.0 nm W/Si and Si/B_4C/W/B_4C reconstructed using Grazing-incidence X-ray reflectivity. (b) reflectance at λ=0.834 nm of 1.0 nm MLs with 100 bi-layers.

NiV-based Multilayer for Soft and Hard X-ray Mirrors

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Nickel is one of the ideal absorption materials in hard X-ray region, therefore, Ni-based multilayer combination is the good choice for monochromator. But nickel is a magnetic material, which is not compatible in magnetron sputtering for small d-spacing multilayers. Except in hard X-ray region, small d-spacing Ni-based multilayer is also used in water window as reflector. For solving this problem, a nonmagnetic alloy was made up of 93% nickel and 7% vanadium has been proposed. As the substitute for Ni-based multilayer, the research of NiV-based ML is limited. In this paper, we report the results of NiV/B4C and NiV/Ti multilayers.

To investigate the influence of background pressure during fabrication, NiV/B4C multilayers were fabricated by magnetron sputtering with different background pressures. The electron dispersive X-ray spectroscopy (EDX) of NiV/B4C multilayer deposited with a high background pressure suggests a gradient distribution of oxygen (shown in Fig.1(a)) which corresponding to the gradient thickness change. The detailed X-ray absorption near edge spectroscopy (XANES) comparison of NiV/B4C multilayers, NiV coating and B4C coating shown the chemical state change induced by background pressure (shown in Fig.1(b)). We found vanadium oxide promoted the oxidation of boron, which induced the thickness change in NiV/B4C multilayer. To compare the optical performance of NiV/Ti and Ni/Ti multilayers at the energy with 420eV, two samples with similar d-spacing were fabricated by magnetron sputtering. As shown in Fig.1(c), the GIXR results show the NiV/Ti multilayer has better interface quality.

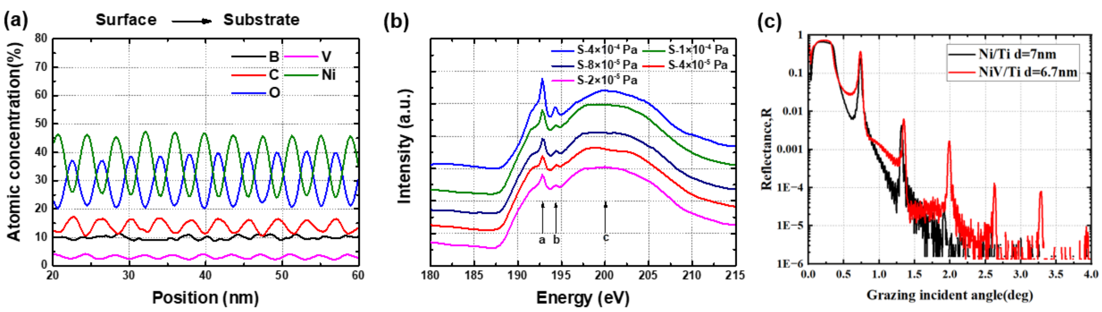

Figure 1. (a) EDX line-scan (from surface to substrate) measurement of chemical elements in NiV/B_4C multilayer; (b) B K-edge XANES spectra of NiV/B_4C multilayer deposited with different background pressures; (c) GIXR results of NiV/Ti and Ni/Ti multilayers.

Wide Bandwidth Neutron-Spin Polarizer Due to Ferromagnetic Interlayer Exchange Coupling

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A neutron-spin polarizing supermirror is one of the most important optical devices to polarize a neutron beam. It is a stack of alternating layers of ferromagnetic (FM) and non-magnetic materials with a variation in bilayer thickness to extend the bandwidth of the neutron polarization. We have developed Fe/Ge polarizing supermirror by using ion-beam sputtering technique. A wide bandwidth is important especially for time-of-flight instruments installed at spallation neutron sources such as the J-PARC MLF since it determines the available wavelength-range of polarized neutrons. The bandwidth can be evaluated by the ratio *m* of the critical momentum transfer of the supermirror to that of nickel to extend the bandwidth. The spontaneous magnetization of the ion-beam sputtered Fe/Ge multilayer, however, disappears when the Fe layer thickness is reduced to 2-3 nm because the Curie temperature becomes to be less than room temperature. This limits the *m*-value of the polarizing supermirror because the multilayer fails to form a high and low contrast in the scattering length density profile for spin-up and -down neutrons. The polarized neutron off-specular scattering measurement of Fe/Ge periodic multilayers revealed that the FM interlayer exchange coupling between neighboring Fe layers grew with decreasing Ge thickness less than 2 nm [1]. The FM interlayer exchange coupling observed here contributed to the presence of the saturation magnetization comparable to the bulk and to smaller coercivity and larger initial permeability than the multilayer without the FM interlayer exchange coupling. This offers a possibility to keep the spontaneous magnetization for the multilayer with a thin bilayer thickness and hence to increase the *m*-value of the polarizing supermirror. We proposed a modified layer sequence of the neutron polarizing supermirror, where the minimum Fe thickness was set to 3.5 nm, whereas the Ge thickness was reduced. A performance test of the neutron polarizing supermirror showed that the FM interlayer exchange coupling contributed to the presence of the magnetization comparable to the bulk and resulted in a marked enhancement in the *m*-value larger than 6. In this presentation, the discussion on the FM interlayer exchange coupling of the Fe/Ge multilayer and its performance as a neutron-spin polarizer will be followed by the one on a recently tested possibility to use an Fe/Cr multilayer for the neutron-spin polarization.

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$^{11}B_4C$-containing Ni/Ti multilayer neutron optics

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Reflective optical elements for both X-rays and neutrons are often made of metallic multilayers. The performance of these mirrors in terms of reflected intensity and accessible operating energy/wavelength range is limited by the finite interface width between the layers. This interface width is primarily caused by a combination of nanocrystallites, formation of intermetallics, intermixing and interdiffusion between neighboring layers, limiting both the optical contrast and the minimum layer thickness that can be achieved in a mirror.

In this work we investigate the effects of different growth conditions on the interface morphology of Ni/Ti based multilayers, with a focus on incorporating low-neutron-absorbing $^{11}B_4C$ and using different ion assistance schemes. We demonstrate how boron-carbon incorporation, in combination with a modulation of the ion-assistance during $^{11}B_4C$ magnetron sputter co-deposition of Ni/Ti multilayers can be used to eliminate nanocrystallites and minimize kinetic roughening.

Grazing incidence small angle X-ray scattering was used to probe the structural and morphological details of buried interfaces, revealing that the layers become more strongly correlated and the interfaces form mounds with increasing amounts of $^{11}B_4C$. Applying high flux ion assistance during growth can reduce mound formation but lead to interface mixing, while a high flux modulated ion assistance scheme with an initial buffer layer grown at low ion energy and the top layer at higher ion energy prevents intermixing. The optimal condition was found to be adding 26.0 at.% $^{11}B_4C$ combined with high flux modulated ion assistance. A multilayer with a period of 48.2 Å and 100 periods was grown under these conditions, and coupled fitting to neutron and X-ray reflectivity data revealed an average interface width of only 2.7 Å, a significant improvement over the current state-of-the-art commercial Ni/Ti multilayers. Overall, our study demonstrates that the addition of $^{11}B_4C$ and the use of high flux modulated ion assistance during growth can significantly improve the interface morphology of Ni/Ti multilayers, leading to improved neutron optics performance.

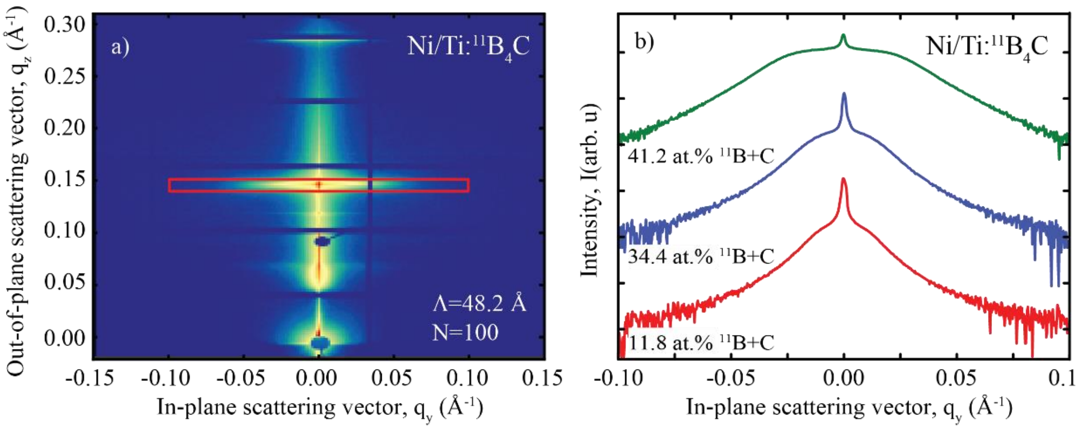

Figure 1. (a) GISAXS intensity map of a $^{11}B_4C$-containing Ni/Ti multilayer. (b) Out-of-plane line scans at the first Bragg sheet of $^{11}B_4C$-containing Ni/Ti multilayers with various amounts of $^{11}B+C$.

Material design optimization for large-m $^{11}B_4C$-based Ni/Ti supermirror neutron optics

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State-of-the-art non-polarizing Ni/Ti supermirror neutron optics suffer from a limited reflected intensity and restricted neutron energy range due to the interface width, which reduces both the optical contrast and the achievable minimum layer thickness in the multilayer stack. This study presents various approaches to optimize the material design of $^{11}B_4C$-containing Ni/Ti supermirrors. Incorporating low-neutron-absorbing $^{11}B_4C$, in combination with high-flux modulated ion assistance, enhances reflectivity and allows for thinner layers to be deposited, leading to the potential for more efficient supermirrors with higher m-values. However, the incorporation of $^{11}B_4C$ reduces the optical contrast, which limits the attainable reflectivity at low scattering vectors where optical contrast plays a crucial role, making this approach unfeasible for supermirrors.

The scattering length density contrast versus interface width for multilayer reflectivity has been investigated, for multilayer periods of 30 Å, 48 Å, and 84 Å, for designs involving pure Ni/Ti multilayers, multilayers with $^{11}B_4C$ co-deposited in both Ni and Ti layers, multilayers with $^{11}B_4C$ co-deposited only in Ni layers, and multilayers with $^{11}B_4C$ deposited as thin interlayers between Ni and Ti layers. Our results suggest that a higher reflectivity than that of state-of-the-art Ni/Ti multilayers can be achieved over the entire scattering vector range by applying a depth-graded hybrid material design. Specifically, this can be accomplished by incorporating $^{11}B_4C$ in the thinner Ni and Ti layers, below approximately 26 Å, and introducing 1.5 Å interlayers of $^{11}B_4C$ between the Ni and Ti layers in the thicker layers.

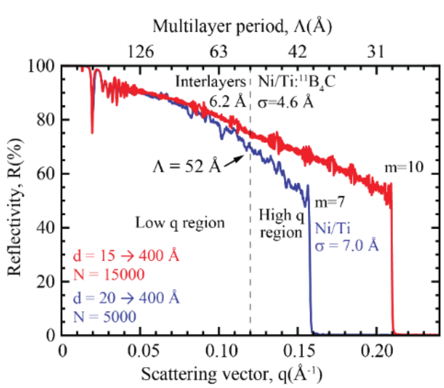

Figure. The calculated performance of a hybrid supermirror design (red) compared to that of a conventional Ni/Ti supermirror(blue).

$^{10}B/^{11}B$-modulated chemically homogeneous boron carbide neutron interference mirrors

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Interface roughness, interlayer chemical reactions, and interdiffusion are the main limiting factors for reaching high reflectivity values from element-modulated neutron multilayer mirrors.
We demonstrate the feasibility of high reflectivity neutron interference mirrors, based on $^{10}B/^{11}B$ modulation as the sole scattering mechanism in chemically homogenous B_xC layers, consequently eliminating any chemical driving force for formation of interphase interlayers and nanocrystallites at the interfaces. Simulations show that the large difference in scattering length density between the two isotopes of B gives the potential for high neutron reflectivities using fewer and thinner layers compared to conventional chemically modulated neutron multilayer mirrors and that absorption effects make them suitable as band-pass mirrors high q-values.
Mirrors with internal $^{10}B/^{11}B$ modulation periods, Λ, ranging from 16 Å to 128 Å with ^{10}B-to-Λ relative thickness ratios, Γ, from 1/8 to 7/8, have been synthesized by alternating magnetron sputter deposition of $^{10}B_xC$ and $^{11}B_xC$ layers producing 128 nm-thick B_xC coatings. Interdiffusion and kinetically limited roughness accumulation was minimized by employing low-energy-modulated (0 eV/~20 eV) high flux ion assisted deposition at room temperature.[1]
Neutron reflectivity (NR) data exhibit clear interference ('Bragg') peaks corresponding to all intended $^{10}B/^{11}B$ modulation periods Λ=16 Å – 128 Å. NR simulations reveal interface widths of ~4.1 Å. The average atomic B/C ratio in the mirrors was determined to x=5.7 with < 1 at% residual elements (O, N, and H) by ToF-ERDA. No traces of elemental modulation or crystallinity were detected by ERDA, X-ray reflectivity, X-ray diffraction, or Transmission Electron Microscopy.
In summary, we have shown that $^{10}B/^{11}B$ modulated chemically homogenous B_xC reflectors can give high reflectivity with relatively few periods which make them suited for high Q bandpass mirrors.

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All-dielectric multilayer mirrors tuned at vacuum ultraviolet wavelengths

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Optics for the FUV (100-200 nm) are challenging in general due to material absorption and the limited knowledge of optical constants. However, this range has gained a renewed interest in space observations and future space observatories like the "Habitable Worlds Observatory, NASA". FUV space instruments require efficient coatings for high-throughput image bandpasses, and, traditionally, MgF_2/LaF_3 multilayers (MLs) have been used, but their optimization is yet to be deeply studied.

Our group, GOLD-IO-CSIC, has developed high-performance all-dielectric FUV coatings with a focus on the short FUV, down to 120 nm, a region with comparatively lower performance due to the increased absorption of fluorides. We present combinations of MgF_2/LaF_3 and AlF_3/LaF_3 that can be tuned for any FUV wavelength >120 nm, with remarkable performance above 85% at H Ly-α (121.6 nm) for AlF_3/LaF_3 MLs (Figure 1 a). We also compare the nanostructural morphologies of the two sets of MLs (Figures 1 b, c) [1].

Below ~120 nm, there is no suitable combination of fluorides since all fluorides but LiF turn absorbing. Therefore, we present narrowband coatings based on Al, LiF, and SiC films, tuned at ~100 nm, with strong rejection at the close H Ly-α line (Figure 1 a) [2].

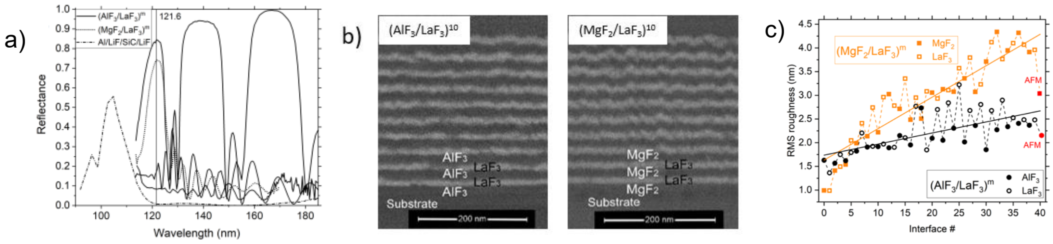

Figure 1 a) Near normal reflectance in the FUV of MLs based on AlF_3/LaF_3, MgF_2/LaF_3, or Al/LiF/SiC/LiF b) Cross-sectional back-scattered electrons SEM images of AlF_3/LaF_3 and MgF_2/LaF_3 MLs, and the retrieved RMS roughness of each interface, from the substrate (#0) to the outermost layer.

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Design Study of Soft X-Ray Aplanat with Four Multilayer Mirrors in Grazing Incidence Configuration

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Enhanced intensity of novel light sources with photon energy between 200 to 700 eV, i.e., higher harmonics and a third-generation synchrotron facility, there is a growing demand for imaging optics that can realize diffraction-limited imaging in these higher energy region. It is known that two spherical mirrors in a grazing incidence layout can provide coma-free focusing in a one-dimensional (meridional) plane. This system convoys the advantages of easy substrate polishing and high reflectivity of a multilayer coating thanks to the grazing incidence layout. If we can extend the system to 2-d imaging, a novel optical design with both high throughput and low aberration in the higher energy region should be expected. This presentation describes the results of a global search for the optical design of a two-dimensional imaging system with four multilayer mirrors in grazing incidence layout.

Figure 1 shows the design example of the four mirror system. The mirror substrates are almost spherical, and small aspherical terms were applied. Novel aspheric terms based on the Zernike polynomials, which are defined by the elliptic area, were introduced. This procedure corresponds to the circular shape of the pupil being stretched into an ellipse on the mirror substrates. It was found that aberrations can be further reduced by using the slight deformations with low-order terms including spherical aberration, coma, and trefoil expressed with the elliptic Zernike polynomials, At the same time, practical high reflectivity of the multilayer coatings should be expected since angle of incidences were assumed to be 60 deg. on each mirrors. In the optimization of the design parameters, first, several two-mirror solutions for 1-d imaging were employed, and we preliminary obtained the initial design of the 2-D imaging system by combining two pairs of the 1-d solutions. Finally, numerical optimization yielded practical solutions that minimize aberration at both the on-axis and off-axis object. As shown in Fig. 1, it was found that the wavefront aberration can be minimized within 100 pm, in the case for numerical aperture of 0.05 and an angle of view of 0.5 degree. In the presentation, we will also report on other interesting design examples found in the design space of the four-mirror system.

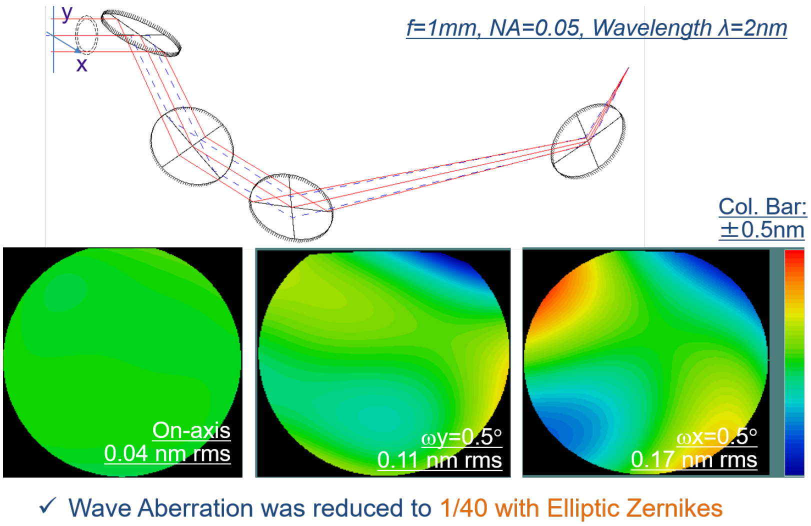

Fig. 1. Design example of four-mirror imaging system with grazing incidence configuration.

Thermally stable $MoN_x/Si_{1-x}N_x$ multilayer as a substrate for XSW study of SMSI

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The Strong Metal Support Interaction (SMSI) is a phenomenon observed in supported metal catalyst systems, in which reducible metal-oxide supports can form overlayers over the active metal nanoparticle (NPs) surface during reduction at elevated temperature in H_2/N_2 environment. X-ray standing wave (XSW) generated using periodic multilayer (ML) can be utilized to study surfaces and buried interface profiles with elemental selectivity at sub-nm scale. Under Bragg condition, standing wave field is formed inside and above the ML giving rise to nodes and anti-nodes. The strength of field intensity is suppressed and enhanced at nodes and anti-nodes respectively. By varying the angle of incidence, position of nodes and anti-nodes can be modulated allowing us to probe surfaces layers and interfaces locally. The stability of ML during the experiment is essential as any expansion or contraction of the bilayers period modifies the XSW and complicates that data analysis, specifically when the comparison of variously prepared samples is required.

For example to study the SMSI effect it is necessary to compare metal-oxide-NPs layer before and after reduction, that requires high-temperature treatment.

In this work, thermally stable ML of $MoN_x/Si_{1-x}N_x$ of 20 periods was prepared to generate XSW and assess the applicability of XSW to study SMSI in Co/TiO_x model catalyst system. The model catalyst system was synthesized on top of ML. By optimizing the ML structure and the TiO_x layer thickness, we achieved maximum sensitivity for the changes in the Ti atomic distribution profile. The samples were reduced under H_2/N_2 environment at 600°C for 1 hour and characterized by a combination of X-ray reflectivity and GIXRF. Partial or full encapsulation of Co NPs by a thin TiO_x layer was identified by monitoring the changes in the phase of the Ti fluorescence signal before and after reduction. The changes in Ti distribution profile upon reduction are shown in figure 1.

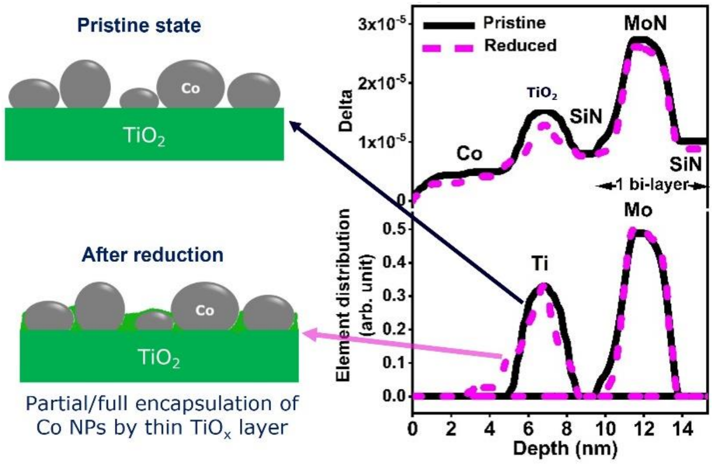

Figure 1. Element distribution and δ profile of the sample Co/TiO_x/ML in pristine state and after reduction.

Author contribution and acknowledgements:

The work was performed in the frame of NEXT3D project funded by TKI Connecting Industry call with the support of Malvern Panalytical.

AT, KM, MA and IM were involved in design and deposition of periodic multilayer, measurements and analysis of X-ray data (2020-2023); MM, LM and FM were involved in the deposition of NPs on ML surface, reduction of the samples and AFM characterisation (2020-2023); SN prepared XSW data analysis algorithm (2020-2021).

Surface roughening by ion beams: Is ballistics "be-all and end-all"?

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Ion beams are commonly used for industrial processing of thin films, ion beam deposition, ion-assisted smoothing or forming layers of compounds. The thin film morphology such as roughness and intermixing with underlying layers are determined by tuning the ion beam energy, flux or angle of incidence. The resulting films may be smooth, rough or may have rippled patterns on the surface. Theoretical formulations have shown ion-surface interactions can be modelled by considering ballistic impacts and energy deposition in the film resulting in the above outcomes. We show that for reactive ion beams of nitrogen and oxygen having similar ballistic impact, the final surface morphology is diametrically opposed. This is hypothesized to be the result of changes in surface diffusivities and cohesive energies between atoms when compounds are formed under reactive ion bombardment. The results could have wider implications in materials processing such as reactive sputter deposition, where tuning surface/interface roughness of compound films may be desirable.

More accurate prediction of optical constants: A prerequisite for the development of next-generation metrology instruments based on soft X-rays

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PTB, Germany's national metrology institute, has been involved in soft X-ray and EUV metrology with synchrotron radiation since 1983 with the start of BESSY. Four decades later, PTB operates several dedicated beamlines at BESSY II and extends the spectral capabilities with its own metrology light source (MLS) into the infrared range. The continuous growth and expansion of these capabilities is closely linked to the increasing relevance and development of EUV lithography by the semiconductor industry. Today, PTB operates several clean rooms, large lubricant-free reflectometers and scatterometers capable of handling large EUV optics. In addition to providing measurement services to customers worldwide, PTB is also developing new solutions for dimensional and analytical metrology in the nanometer regime using soft X-rays and EUV radiation. Bringing metrology solutions based on light-matter interactions into the sub-nm precision range requires well-controlled experiments and extensive modelling of the entire experimental chain. Precise knowledge of the material parameters is a key factor in creating an accurate virtual optical response that can describe and simulate the measurements. In addition to the shrinking size of the latest 2D and 3D nanostructures, the increasing number of material mixtures undergoing complex manufacturing processes poses new challenges. Oxidation, contamination, impurities, or density variations can have a huge impact on the optical constants. In addition, material properties of compound materials and alloys need to be measured since for many cases their refractive index cannot be predicted using data of the individual components. The Optical Constants Database (OCDB) project at PTB tries to bridge the gap between existing data sets, including reliable uncertainties. New developments in X-ray metrology are being driven by the need to further reduce uncertainties in dimensional metrology in the lower sub-nm range. We review recent advances in X-ray scattering (GISAXS, EUV-SAS) and the hybrid use of X-ray fluorescence techniques (GIXRF, GEXRF) to further increase the required sensitivities and discuss how these techniques can be transferred from large-scale research facilities to the laboratory.

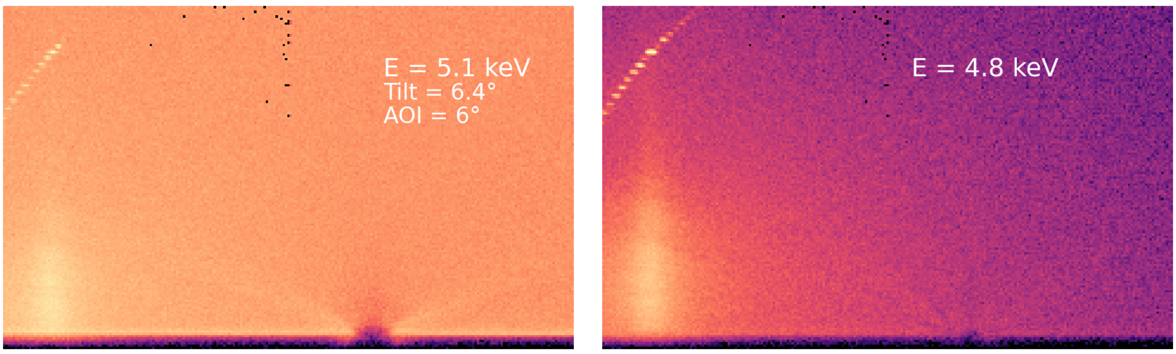

Fig 1: Combined X-ray scattering and GEXRF from a lamellar TiO_2 grating structure

Bayesian Inferences and Time-Frequency Analysis Assisted Determination of Optical Constants in the EUV

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Next-generation EUV Lithography (EUVL) scanners with a Numerical Aperture (NA) of 0.55 are now in production, realizing an 8 nm half-pitch with one exposure is now possible [1]. Technologies like EUV ptychography and scatterometry are spreading. These developments necessitate accurate optical constants and relevant metrological capabilities. Optical constants are indispensable in the design of optical elements and metrology is required for their characterization and defect-inspection.

The method of choice in PTB to determine optical constants is reflectometry. It allows simultaneous determination of both parts of the complex refractive index from multilayers, thin films and substrates, at any wavelength. Reflectometry supports an “at-wavelength metrology” approach since most optical elements used for EUV applications are rather reflective. These benefits cannot be realized using other known methods like Transmission Mode Measurements (TMM) and Electron Energy Loss Spectroscopy (EELS). However, determining optical constants from reflectivity data requires the convergence of a model-based inverse-problem. The method is susceptible to contamination, oxidation and imperfections of the sample such as surface roughness. To mitigate these limitations, the relevant inverse-problem targeting optical constants in the EUV range is complemented with X-ray Reflectivity (XRR) data. XRR is known for the high sensitivity to the geometrical characteristics providing sub-nanometre resolution. Time-Frequency Analysis (TFA) of XRR data is one option for directly inferring geometrical information about the sample circumventing classical trial-and-error approaches. Initializing the inverse-problem for determining optical constants in the EUV using a model based on XRR data supports obtaining highly accurate results.

Recently, Markov Chain Monte Carlo (MCMC) based Bayesian inferences of EUV data were coupled TFA of XRR to determine highly accurate optical constants – with uncertainties – of many materials, including ruthenium and cobalt [2, 3].

Our contribution shows additional details of PTB metrology and modelling latest capabilities for determining optical constants, with emphasizing the impact on future development of optical elements dedicated for the soft X-ray and EUV spectral ranges [4].

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Refractive index measurements with improved accuracy for EUV/x-ray multilayer optics

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EUV/x-ray multilayer optics with complex structures and functionalities have become key components for various applications including photolithography, plasma physics, synchrotron, laser and ultrafast science, solar physics and astrophysics. Yet, the available refractive index values required to design and fabricate these optics, are often unreliable [1]. This is due to challenges inherent to the EUV/x-ray spectral region, such as the extreme sensitivity of materials to contamination and oxidation, the difficulty in fabricating appropriate thin film samples, the presence of near-edge absorption fine structure, and the presence of multiple reflections at the longer EUV wavelengths, which are complicating the measurements.

We are presenting a new methodology to measure the EUV refractive index and new sets of measurements for several important EUV/x-ray materials including Al, Cr, W, Pt [2-4].

We use combinations of transmittance and reflectance data in the spectral range 1.5 nm to 82.5 nm and demonstrate for the first time highly resolved fine structure in the regions of L, M, N and O absorption edges, in both the absorptive and dispersive portions of the refractive index, resulting in improvements of up to a factor of 3 compared to earlier values. The improved refractive index accuracy is validated by fitting experimental reflectance and transmittance data of multilayer coatings containing these materials. The development of new and improved measurement methodologies and the resulting new refractive index datasets will enable the accurate design, implementation and modeling of the in-band and out-of-band performance of the next generation of EUV/x-ray optics.

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Poster Session

Enhancement of Diffraction Efficiency and Spectral Flux with Quasi-Graded Index Coating (QGIC) on Soft X-Ray Laminar-Type Diffraction Gratings Optimized for B-K and Li-K Emissions

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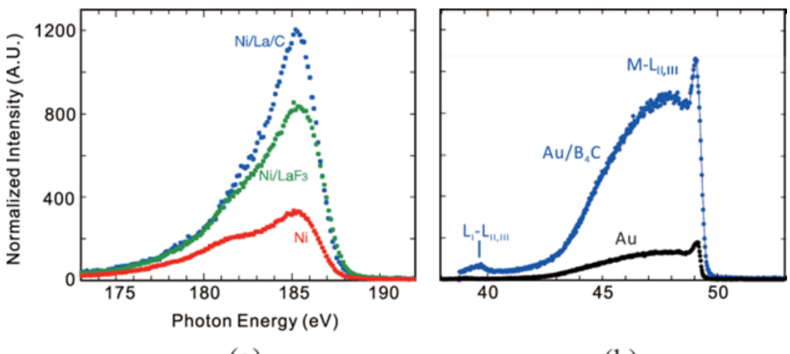
A quasi-graded index coating (QGIC) to enhance the diffraction efficiency and spectral flux [1] of soft x-ray gratings used at grazing incidence satisfying total reflection was investigated. The QGIC grating consists of a laminar-type grating, metal coating on the grating grooves, and additional overcoating(s) having intermediate refractive indices between vacuum and the metal coating. (Table 1) The QGIC gratings optimized for B-K (183.3 eV) and Li-K (54.3 eV) emissions were designed and fabricated. For the experimental evaluation of the performance of the QGIC the use was made of a soft x-ray flat-field VLS spherical grating spectrograph installed to an electron microscope. The intensity observed with a CCD detector was normalized by the acquisition time and the beam current. Figure 1 (a) shows B-K spectra of β-rhombohedral B observed with an angle of incidence fixed to 84.8°. Ratio of the integrated spectral intensities were 1.0 : 2.0 : 2.5 for Ni, Ni/LaF_3, and Ni/La/C coatings [1]. Figure 1 (b) shows the Mg-L (39.3 and 49.3 eV) spectra of metal Mg observed with Au and Au/B_4C coated gratings at the angles of incidence of 86.0° and 84.0°, respectively.

Table 1. Complement refractive indices ($\delta = 1.0-n$) at 183.3 and 54.3 eV.

183.3 eV (B-K)	
Vaccum	0.00000
C	0.00892
LaF_3	0.01597
La	0.01669
Ni	0.02522

54.3 eV (Li-K)	
Vaccum	0.00000
SiC	0.08121
B_4C	0.10302
Au	0.14974



(a) (b)

Figure 1. Normalized intensities of (a) B-K emission spectra of β-rhombohedral B observed using Ni-, Ni/LaF_3-, and Ni/La/C-coated diffraction gratings,[1] and (b) Mg-L emission spectra of metal Mg observed using Au-, and Au/B_4C-coated diffraction gratings.

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Development of Narrowband Multilayer Mirrors for Extracting a Single Harmonic from an EUV HHG Source

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We developed a Y/AlSi multilayer with narrowband performance in order to extract a pure single harmonic from HHG (High Harmonic Generation). The multilayer was optimized for 63.8 eV (53rd order), enabling the probing of the $M_{2,3}$ absorption edges of the 3d transition metals such as Mn, Fe, and Co. Its performance and thermal stability were compared with another EUV mirror, Zr/AlSi multilayer, which has shown good performance in the EUV region (50-73 eV). Y/AlSi multilayers with different structure parameters were also examined. All multilayers were evaluated by measuring incident EUV reflectance at ALS beamline 6.3.2 and X-ray reflection (XRR).

Figure 1 shows the measured reflectance of Y/AlSi and Zr/AlSi multilayer mirrors at an incidence angle of 3°. The measured peak reflectance of Y/AlSi and Zr/AlSi multilayers are 43% at 64 eV and 52% at 63.8 eV, and the energy bandwidth (FWHM) of the reflectance curve were 1.7 eV and 2.5 eV, respectively. Our results show that the Y/AlSi multilayer mirror can better suppress adjacent harmonic lines while still having sufficient reflectivity for the selected single harmonic. There is no significant drop in reflectance of both multilayers after heating up to 200 °C and no deterioration of multilayer structure were observed after storage in air for 5 months.

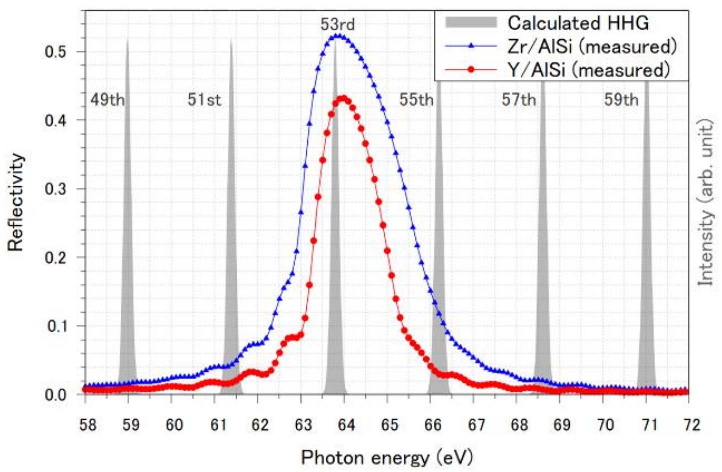

Figure 1. Comparison of the calculated HHG spectra (grey filled areas) and the measured EUV reflectivity for Zr/AlSi (blue points) and Y/AlSi (red points) multilayers.

Resolving buried interfaces by Low-Energy Ion Scattering

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X-ray optics is based on reflective multilayers with layer thicknesses of a few nanometers at most. The interface quality plays a central role in determining the final properties of these structures. However, the accurate characterization of such interfaces with the necessary quasi-atomic resolution is a challenge. In this context, Low Energy Ion Scattering (LEIS) plays a crucial role because it provides a unique way to measure both the elemental composition of the outer atomic layer and the subsurface elemental distribution.

In LEIS, ions scattered by subsurface atoms undergo charge transfer processes in addition to scattering. They have a high probability of being neutralized while penetrating the solid and a low probability of being re-ionized upon leaving the surface. The low reionization probability creates a clear contrast between the surface peak and subsurface tail. While the scattering processes are well known, the charge transfer processes that influence the tail shape are still not fully comprehended. Consequently, the correlation between tail shape and in-depth composition is still unresolved.

In this work, we study one of the charge transfer phenomena, reionization, by comparing experiments and Monte Carlo simulations. The study is performed on bulk Si and Si thin films deposited on W or Mo. We show how the energy-dependent reionization probability of Si can be used to simulate LEIS spectra of structures with Si as the top material. With this approach, we manage to resolve the buried interface between the thin films with a sensitivity of a fraction of a nanometer.

Fabrication and characterization of EUV multilayer gratings

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By matching multilayer Bragg interference and grating diffraction conditions, EUV multilayer gratings provide high spectral resolution ($\lambda/\Delta\lambda$ > 1000) with efficiencies similar to the reflectance of the multilayer coating. Such components are of particular interest for EUV spectro-imaging application. In this work, we optimized and studied periodic multilayer on gratings with trapezoidal shape in order to reach a maximum 1st order efficiency at wavelengths ranging from 25 nm to 29 nm, a region of particular interest for solar corona spectro-imaging [1]. We have recently reported on Al/Mo/SiC multilayer diffraction gratings with broadband efficiency in the extreme ultraviolet [2]. We report here on the fabrication and characterization of the groove profile evolution after deposition using TEM and AFM analyses. Different kind of multilayers have been deposited by magnetron sputtering [3] and ion beam sputtering [4] on grating substrates with high groove density (> 3600l/mm). We used both fused silica grating substrates provided by Zeiss (holographic process) and silicon grating substrates processed in our lab via e-beam lithography. The results obtained with different material combination for the multilayer, different grating substrates and different deposition technics will be discussed and compared.

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EMIL@BESSY-II: In-situ investigations of material combinations at a synchrotron light source

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The Energy Materials In-Situ Laboratory Berlin (EMIL) at BESSY-II combines modern techniques of thin film/layer deposition with the possibility of in-situ characterization tools like (Hard X-ray) Photoelectron Spectroscopy, X-Ray Absorption and Emission Spectroscopy and X-Ray Fluorescence Spectroscopy. The experimental endstation, lab-based x-ray spectroscopy, and layer deposition facilities are connected via an UHV-transfer backbone: samples can be transferred under vacuum conditions to the endstation, characterized, and taken back to a deposition tool for further processing. This infrastructure allows for a step by step production and analysis of different material combinations. Magnetron sputtering, e-beam evaporation, atomic layer deposition and chemical vapor deposition tools are available within the interconnected UHV system for different applications. In combination with the wide energy range of 80eV – 10keV of the EMIL beamline, which is fed by a canted double undulator system and equipped with three monochromators, depth information from the surface down into the bulk up to 5µm are accessible.

We will show the current setup and performance, possible material combinations and some results of recent measurements. EMIL has been in user operation since 2020 and welcomes interested users.

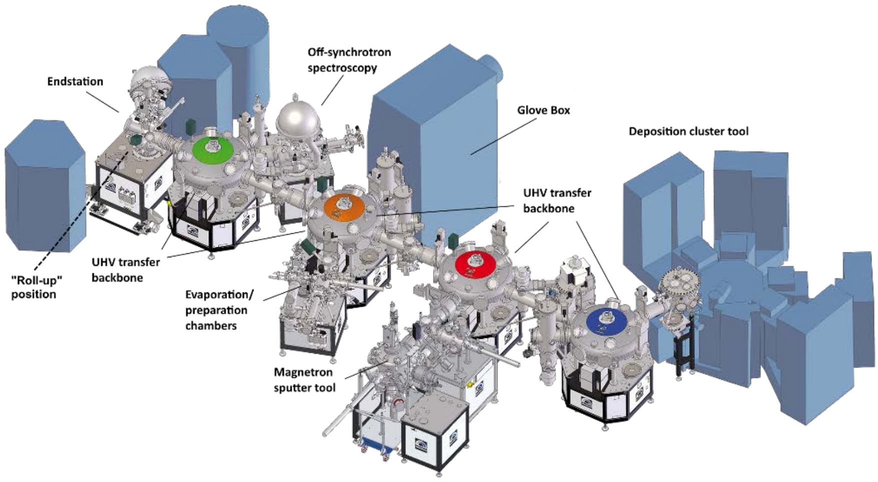

Figure 1: EMIL endstation, the UHV-transfer backbone and deposition facilities

Upgrades of PTB’s EUV Reflectometry Instrumentation

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With increasing demand for EUV Lithography, optical elements and sensors for EUV radiation are needed for a multitude of instruments and machines in its supporting ecosystem. Most of these systems require at-wavelength characterization supporting development, manufacturing, utilization and maintenance.

PTB provides at-wavelength characterization metrology services in the EUV spectral region for 40 years now. The requirements of the partners from research and industry increased ever since and PTB is continuously upgrading its instrumentation. PTB now put into operation a lubricant free reflectometer, designed to handle sample sizes of “collector” type mirrors up to 670 mm in diameter and 250 mm in height and “long mirror” type samples of 1000 mm x 150 mm x 250 mm with up to 150 kg in weight combined for sample and mounting to support the characterization of production grade optical elements in the 6 nm to 40 nm wavelength range.

We present our large lubricant free reflectometer at PTB’s MLS (Metrology Light Source) synchrotron laboratory, as well as its supporting infrastructure and peripherals.

Preferred presentation: Poster

Optical Constants of Carbon and Boron material for Beyond EUV Lithography

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In 2019, EUV lithography technology with a wavelength of 13.5 nm was first applied to mass production of 7 nm+ node logic devices. In the future, since semiconductor devices with higher-density electronic circuits are required, beyond EUV (BEUV) lithography technology with an exposure wavelength around 6.7 nm is expected as the next generation lithography. The development of multilayer with high reflectivity is a critical issue for BEUV lithography.

The calculated reflectance spectra of the multilayers for BEUV are shown in Fig. 1. La/B-based multilayers, which have been developed, have a high theoretical reflectivity of about 80%. The highest reflectance of 64.1% was reported for LaN/La/B multilayer at the angle of incidence (AOI) of 1.5° [1]. However, it is difficult to achieve high temporal stability in La/B-based multilayers because of the high chemical activity of La. Thus, we propose Carbon/Boron (C/B) multilayer as a new BEUV multilayer. The performance of the C/B multilayer is comparable to that of the La/B multilayer. The optical constant of the carbon film depends on its density, and high-density C has good optical constant for BEUV multilayer. In the calculation of Fig. 1, the density of 3.1 g/cm^3 was used, which is the highest density of diamond-like carbon film. For the C/B multilayer fabrication, we have deposited C and B layers, and measured actual optical constants at BEUV using a reflectometer in NewSUBARU synchrotron light facility. The measurement results of optical constants are shown in Fig. 2. We will discuss the performance of the C/B multilayer based on the results of theoretical calculations and measured optical constants.

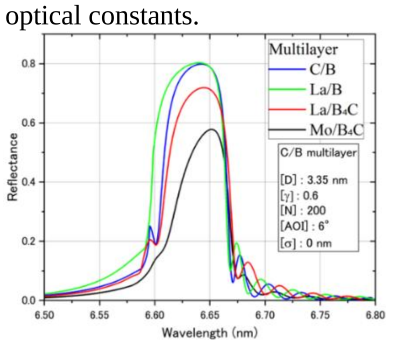

Figure 1. Calculated reflectance spectra of BEUV multilayers.

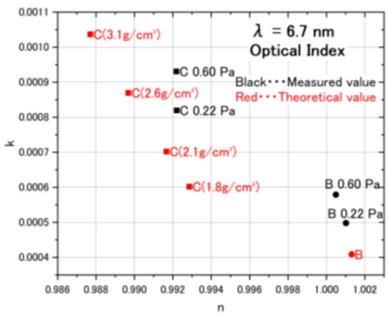

Figure 2. Measurement results and calculated value of optical index at 6.7-nm wavelength.

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Improved performance of polarizing Fe/Si multilayer neutron optics by $^{11}B_4C$ incorporation

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Polarized neutrons provide valuable insights in magnetism, materials science, and biology. However, polarizing multilayer neutron optics have limitations such as low reflectivity and polarization, especially at higher scattering vectors/angles, and dependence on high external magnetic fields for magnetization. We addressed these issues by co-depositing $^{11}B_4C$ to Fe/Si multilayers during ion-assisted magnetron sputter deposition. Our research shows that integrating $^{11}B_4C$ into Fe/Si multilayers leads to amorphous multilayers with smoother interfaces, improving neutron reflectivity and polarization. Furthermore, the $^{11}B_4C$ allows for scattering length density tuning for optimal polarization. This improvement was demonstrated using X-ray and reflectivity (XRR) and polarized neutron reflectivity (PNR). The incorporation of $^{11}B_4C$ reduced diffuse scattering, evidenced by grazing incidence small-angle X-ray scattering (GISAXS), and eliminated the magnetic coercivity, observed through vibrating sample magnetometry (VSM) and magneto-optical Kerr effect (MOKE) measurements, rendering the multilayers magnetically soft, enabling magnetic saturation at low external fields. By successfully addressing the limitations of polarizing multilayer neutron optics, the integration of $^{11}B_4C$ into Fe/Si multilayers offers a promising approach for improving the performance and functionality of neutron scattering facilities.

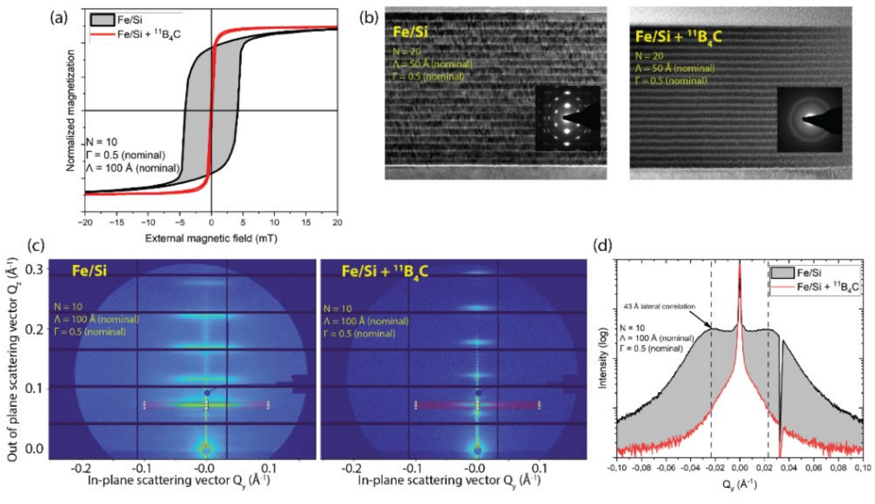

Figure 1. Fe/Si and Fe/Si + $^{11}B_4C$ comparison. (a) VSM. (b) TEM. (c) GISAXS raw data. (d) Out-of-plane line cuts.

Removal of Mo/Si Multilayer Coatings on Fused Silica Substrates by Wet Chemical Etching

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Mo/Si multilayer mirrors operating in the 13-nm wavelength region can provide a high reflectivity of over 60% and have been applied in numerous imaging systems, such as extreme ultraviolet (EUV) microscopy instruments. These mirrors have a multilayer structure comprising Mo and Si bilayers on a super-polished substrate that is typically made of fused silica or ultra-low-expansion glass. An iterative and time-consuming polishing process is employed to fabricate such substrates, since the figure error must be controlled with a spatial period between several hundred millimeters and several micrometers. The surface figures in the low- and high-frequency regions are commonly controlled by either bowl-feed polishing[13)] or state-of-the-art numerical control techniques, such as magneto-rheological finishing, combined with interferometric surface figure measurements. However, these processes are both labor-intensive and expensive. One promising approach to reducing costs and labor requirements is to reuse mirror substrates, by completely removing the original multilayer coatings and depositing new ones. The reuse of such mirrors could be considered when the mirror itself shows damage, such as oxidation of the top surface layer by contact with ambient air, carbon contamination resulting from intense EUV irradiation or thermal diffusion in the periodic structure. These types of damage will eventually degrade the reflectivity of the device. During reuse processing, the multilayer coating must be completely removed while keeping the shape of the mirror substrate unchanged, and several studies have examined techniques for removing Mo/Si multilayer structures with surface oxide layers or carbon contamination. However, to the best of our knowledge, there have been no reports concerning techniques for removing the entire multilayer structure from the substrate. In the present work,[1)] we demonstrate a novel method for completely removing Mo/Si multilayer coatings, based on wet chemical etching. This research examines an etchant capable of dissolving both Mo and Si at a sufficiently high etching rate with little effect on fused silica (SiO_2) substrates. Specifically, a Mo/Si multilayer mirror was immersed in an alkaline solution containing potassium ferricyanide ($K_3Fe(CN)_6$) and sodium hydroxide (NaOH), which was found to remove the entire coating. The surface shape of the substrate was then evaluated using an optical profiler to confirm that the etching process did not increase the surface roughness.

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Picometer Sensitivity on Laboratory-based XRR Instrument Equipped with Fast and Accurate Sample Alignment System

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X-ray reflectometry (XRR) is a powerful non-destructive evaluation method for density profile of multilayer structure, e.g., EUV and X-ray optics which have artificial superlattice structures to select the specific wavelength. XRR measurements are performed with grazing incidence and exiting geometry, thus it requires precise sample position and incidence angle alignment before measurements, but it is a time-consuming process due to iterate some scans although obtaining better reproducible and repeatable measurement results. In this study, we demonstrated that the capabilities of commercially available X-ray diffraction platform for such XRR applications with superb picometer sensitivity with fast and accurate sample alignment system for EUV optics samples.

XRR measurements were performed on Bruker D8 DISCOVER materials research X-ray diffraction platform which can supply tailored solutions for multiple samples from R&D leveled small pieces to industrial scale wafer samples. X-ray is generated in the industrial-grade sealed tube with Cu target, and convergent into highly paralleled beam by using Göbel multilayer mirror to select CuKα wavelength with less than 0.028° divergence. The primary beam size was precisely controlled by motorized cross-slits with 0.001 mm resolution. Samples were horizontally mounted on vacuum chuck stage which is made of porous ceramics material to avoid sample bending. Beam knife-edge was also equipped on the sample surface which has height sensor to control sample surface position and knife-edge gap space automatically. In secondary, inverted Göbel multilayer mirror was mounted and reflected X-rays were collected by semiconductor-based X-ray detector without any attenuator. The configuration with two symmetrically placed Göbel mirrors guarantees the highest insensitivity to beam profile changes and to small sample misalignments. This is ideal for high reproducibility of the measurements and allows the possibility of changing the beam shape during different part of the same curve. The measured sample size was 25×25 mm and axial slit size was kept as 16 mm. Equatorial slit and knife-edge gap sizes were precisely controlled depending on the scan 2θ angles in 3 steps, 0.2 and 0.025 mm in 0-2.2°/2θ, 0.2 and 0.1 mm in 1.8-7.2°/2θ, and 1.2 and 0.6 mm in 6.8-17°/2θ, respectively. Scan integration time and increment were kept as 0.1 s/step and 0.01°/step.

Sample shows clearly sharp superlattice satellite peaks up to 12 orders in 17°/2θ. The typical reproducibility result was < 0.001° in standard deviation at 7.5°/2θ. This deviation is corresponding to 1 pm for the superlattice periodic thickness. We will show more detail information in the session.

Samples were courtesy supplied from optiX fab GmbH.

At-Wavelength Metrology for diffractive and reflective optics in the EUV, XUV and tender X-ray energy range

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An accurate characterization of the real performance of sophisticated reflective or diffractive optics is extremely demanding to experimental conditions task. An At-Wavelength Metrology facility for EUV and XUV optics is under operation since many years at the BESSY-II storage ring. As the main instrument a versatile 11-axis UHV-reflectometer is permanently connected to a dedicated Optics beamline. The setup is suitable for measurements as well as on small test samples but also for real size optics in limits up to 360 x 60 x 60 mm3. Moreover, a flexible sample stage support system based on an UHV-tripod gives 6 degrees of freedom for a precise alignment and mapping of optical elements under test. 360 degrees freedom goniometers enable to bring the beam on the sample in incident angle from 0 to 88.9 degree and scan outgoing radiation in almost complete in-plane circle as well to continuously rotate whole system from s to p polarization geometry. High spectral purity of the incident beam is achieved by a set of 12 absorption filters and a High-Order Suppressor System. It was experimentally tested that it gives a nearly high-order free beam between 13.5 eV and 1800 eV. In additional to that a small Reflectometer as a portable end-station is used to get access to UV-EUV or X-ray energy ranges by setting it up at U125-2_NIM (4eV – 30eV) and KMC-1 (2keV – 10keV) beamlines at BESSY-II. The present status of the metrology facility, their latest upgrade projects and most challenging results will be presented in our contribution.

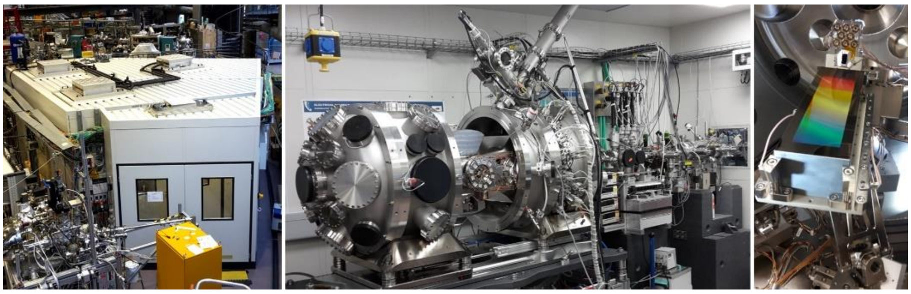

Figure 1. Optics beamline hutch, 11-axis UHV-reflectometer outside and inside view.

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Low-Cost Cleaning Method of Mo/Si Multilayer Soft X-ray Mirrors Using a Wet Process

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A low cost cleaning method of Mo/Si multilayer soft X-ray mirrors using a wet process with NaOH solutions were investigated for the realization of reusing and prolonging the lifespan of soft X-ray mirrors. The effectiveness of the cleaning method is examined by reflectivity and X-ray photoelectron spectroscopy (XPS) measurements of Mo/Si multilayers on SiO_2 substrates. The Mo/Si multilayers surfaces were intentionally oxidized and carbon contaminated by the storage in the atmosphere and carbon deposition for the usage of these mirrors as models of the oxidized and carbon contaminated mirrors. The wet process cleaning was carried out by immersing the oxidized and carbon contaminated mirrors into NaOH solutions. The mirrors were rinsed by ultrasonication with isopropyl alcohol and acetone after the immersing. In this presentaion, we report results of the changing of the reflectivity and the surface chemical composition of the mirrors.

Figure 1 shows the XPS spectra taken from the carbon contaminated mirror, oxidized mirror and mirror after the cleaning. On the mirror surface after the oxidation or carbon contamination, peaks derived from the molybdenum oxides or carbon appear dominantly. In contrast, on the mirror surface after the cleaning, peaks derived from the metal molybdenum appear, which imply that mirrors after the cleaning process have less contaminations and a possibility to exhibit higher reflectivity than those storaged in the atmosphere. In the poster presentation, we explain the relation between XPS and reflectivity measurements results in detail.

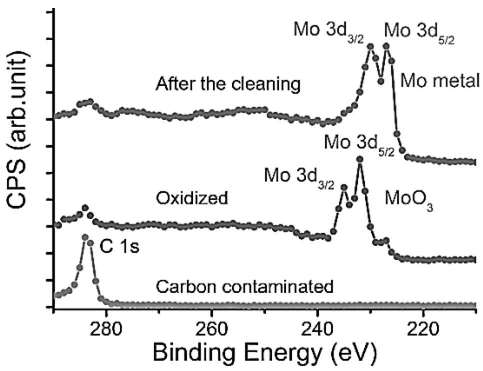

Figure 1. XPS spectra taken from the carbon contaminated mirror, oxidized mirror and mirror after the cleaning (from bottom to top).

High Irradiance Illuminator for Transmission Extreme Ultraviolet Microscopy

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We are developing a lab-scale transmission extreme ultraviolet (EUV) microscope using a laser-produced plasma (LPP) light source operating at a wavelength of 13.6 nm. The microscope is made of an illuminator and a two-stage magnifying objective, that are all consisting of five Mo/Si multilayer mirrors. We have reported good elemental contrast between oxygen and carbon on polymer samples; a transmission image observation allows visualization of the phase-separated structure of PS/PMMA polymer blends without staining [1]. High intensity illumination should be one of the keys to achieve diffraction-limited imaging on the lab-scale microscope. A limited brilliance of the light source tends to increase a photon noise on images and spoils the spatial resolution. Therefore, we developed a novel two-aspherical-mirror system providing high intensity illumination, as shown in Figure 1. The system can provide lager solid angles by correcting a spherical aberration, which is inherent in the previous system with spherical mirrors. In this presentation, first, we provide results of numerical calculations to estimate the enhanced intensity, where, as well as geometric optics, we treat two practical contributions given from experiments, i.e., the luminance distribution of the LPP light source and reflectance of the Mo/Si multilayer coating. The luminance distribution was obtained by imaging the light source with an EUV microscope, and the reflectance of the multilayer mirror was measured with an EUV reflectometer [2] in our laboratory. We will also report the comparison of experimental results for intensities on sample plane, that are given with the aspherical and spherical illumination systems as shown in Figure 2.

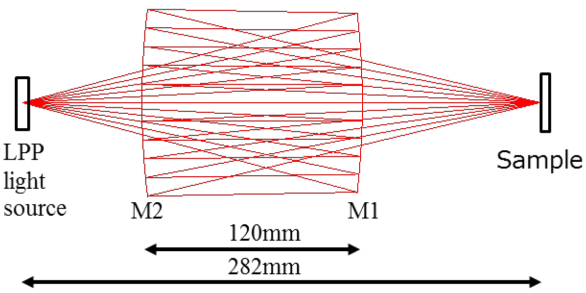

Figure 1. Schematic diagram of a two-plane aspheric illumination optical system.

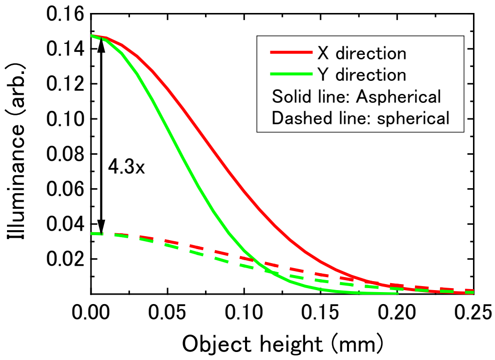

Figure 2. Calculation results considering reflectance of multilayer mirror and luminance distribution of LPP light source.

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Multilayer structures in coherent x-ray diagnostics in BISER and Relativistic Flying Mirror experiments

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We are developing bright compact temporally and spatially coherent x-ray sources based on Burst Intensification by Singularity Emitting Radiation (BISER) and Relativistic Flying Mirror (RFM) concepts. BISER [1-2] is the emission of bright coherent x-rays by multi-stream flow singularities produced in a relativistic plasma by high-power lasers. The RFM [3-5] is a mirror moving nearly at speed of light formed by an intense laser in underdense plasma. A counter-propagating laser pulse partially reflects from the RFM, with its wavelength and pulse duration compressed by a large factor up to $\sim 4\gamma^2$ resulting in bright coherent x-rays.

We present x-ray diagnostics used in our BISER and RFM experiments based on multilayer structures: spectrographs with aperiodic broadband multilayer mirrors [6] (12.4-25 nm) and a 3-channel spectrograph with a multilayer-coated laminar VLS grating [7] (1-2 keV).

Acknowledgments

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A new variant of high-performance neutron supermirror polarizer

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Being the world's leading facility in neutron science and technology, the ILL makes its facilities and expertise available to about 1400 researchers per year, performing 1000 experiments in a wide range of scientific fields. In an ever-growing part of these experiments, the possibility to produce spin-polarized neutron beams is exploited to pinpoint magnetic information much more precisely. In this context, designing and producing high-performance neutron polarizers and analyzers if essential. One of the widespread neutron polarizing technologies consists in using broadband interferential multilayer mirrors called "supermirrors". Driven by the need of a "near-perfect full-beam" polarization for neutron experiments in fundamental physics [1], we have been developing a new variant of supermirror-based polarizer, that pushes the limit of performance further and offers practical advantages. It is based of Fe/Si supermirrors coated on sapphire single crystal substrates, thus getting around the coating activation and substrate degradation issues, while improving the accepted neutron bandwidth [2]. By taking special care to the geometrical design, the magnetic circuit, the coating process and the mounting procedure [3], a record-breaking full-beam polarization of 99.7% with a 31% transmission was measured for the wavelength range 0.3 – 20 nm [Figure 1]. The final device is now available for users on the PF1B instrument. While the same polarizer design could be used for other types of instruments by tuning the geometry, in the case of a largely different instrumental configuration most of the concepts can be kept. Indeed, we are installing a new analyzer on the polarized neutron reflectometer D17, which only differs from the PF1B device by its geometrical design. It will allow broadband high-efficiency polarization analysis both in the case of specular and off-specular measurements.

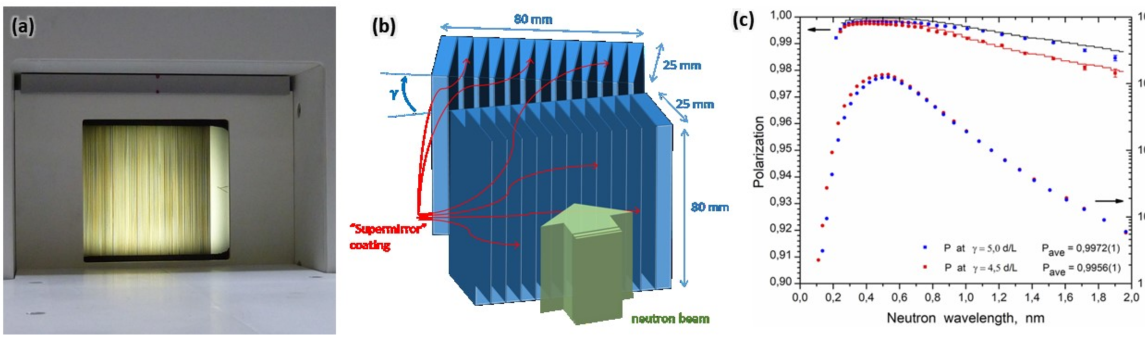

Figure 1. Photograph (a) and schematic view (b) of the polarizer for PF1B. Measured performance of the polarizer (c) in terms of full beam polarization efficiency and output flux density for two values of angle γ between successive cassettes.

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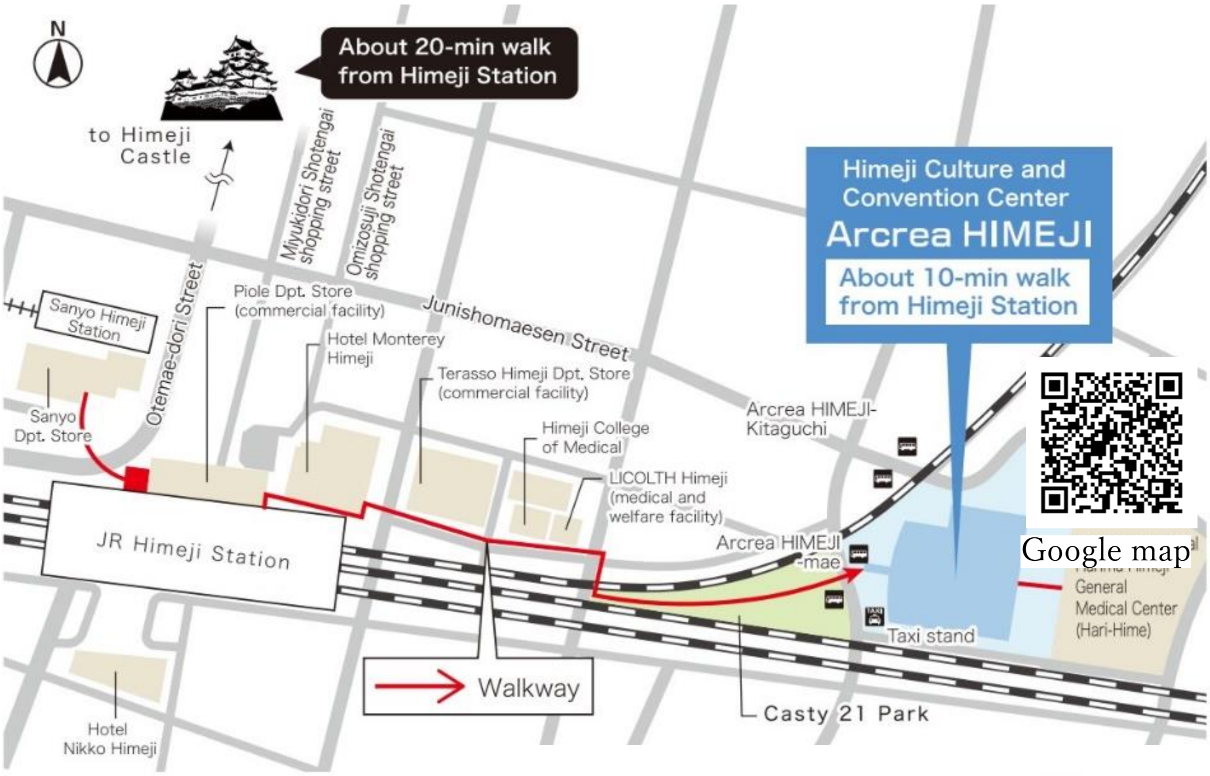

Excursion Bus Arrival &
Banquet Bus Departure Place

Google map

Wifi: Himeji-CCC
Password: 0792638082

Oral Session:
2F Medium Hall

Poster Session &
Communication Party:
2F Foyer of Medium Hall

Lunch:
4F Meeting Room 409

Excursion Bus Departure:
1F Outside of West Entrance