

PROCEEDINGS OF SPIE

Damage to VUV, EUV, and X-Ray Optics II

Libor Juha
Saša Bajt
Ryszard Sobierajski
Editors

21–23 April 2009
Prague, Czech Republic

Sponsored by
SPIE Europe

Cooperating Organizations
Institute of Physics, Academy of Sciences (Czech Republic)
Department of X-Ray Lasers, Institute of Physics (Czech Republic)
Czech and Slovak Society for Photonics
Photonics Society of Poland (Poland)

Published by
SPIE

Volume 7361

Proceedings of SPIE, 0277-786X, v. 7361

SPIE is an international society advancing an interdisciplinary approach to the science and application of light.

The papers included in this volume were part of the technical conference cited on the cover and title page. Papers were selected and subject to review by the editors and conference program committee. Some conference presentations may not be available for publication. The papers published in these proceedings reflect the work and thoughts of the authors and are published herein as submitted. The publisher is not responsible for the validity of the information or for any outcomes resulting from reliance thereon.

Please use the following format to cite material from this book:

Author(s), "Title of Paper," in *Damage to VUV, EUV, and X-Ray Optics II*, edited by Libor Juha, Saša Bajt, Ryszard Sobierajski, Proceedings of SPIE Vol. 7361 (SPIE, Bellingham, WA, 2009) Article CID Number.

ISSN 0277-786X
ISBN 9780819476357

Published by

SPIE

P.O. Box 10, Bellingham, Washington 98227-0010 USA
Telephone +1 360 676 3290 (Pacific Time) · Fax +1 360 647 1445
SPIE.org

Copyright © 2009, Society of Photo-Optical Instrumentation Engineers

Copying of material in this book for internal or personal use, or for the internal or personal use of specific clients, beyond the fair use provisions granted by the U.S. Copyright Law is authorized by SPIE subject to payment of copying fees. The Transactional Reporting Service base fee for this volume is \$18.00 per article (or portion thereof), which should be paid directly to the Copyright Clearance Center (CCC), 222 Rosewood Drive, Danvers, MA 01923. Payment may also be made electronically through CCC Online at copyright.com. Other copying for republication, resale, advertising or promotion, or any form of systematic or multiple reproduction of any material in this book is prohibited except with permission in writing from the publisher. The CCC fee code is 0277-786X/09/\$18.00.

Printed in the United States of America.

Publication of record for individual papers is online in the SPIE Digital Library.

SPIE 
Digital Library

SPIDigitalLibrary.org

Paper Numbering: Proceedings of SPIE follow an e-First publication model, with papers published first online and then in print and on CD-ROM. Papers are published as they are submitted and meet publication criteria. A unique, consistent, permanent citation identifier (CID) number is assigned to each article at the time of the first publication. Utilization of CIDs allows articles to be fully citable as soon they are published online, and connects the same identifier to all online, print, and electronic versions of the publication. SPIE uses a six-digit CID article numbering system in which:

- The first four digits correspond to the SPIE volume number.
- The last two digits indicate publication order within the volume using a Base 36 numbering system employing both numerals and letters. These two-number sets start with 00, 01, 02, 03, 04, 05, 06, 07, 08, 09, 0A, 0B ... 0Z, followed by 10-1Z, 20-2Z, etc.

The CID number appears on each page of the manuscript. The complete citation is used on the first page, and an abbreviated version on subsequent pages. Numbers in the index correspond to the last two digits of the six-digit CID number.

Contents

- ix *Conference Committee*
- xi *Introduction*
- xv *Photon physics: from wave mechanics to quantum electrodynamics (Plenary Paper)*
[7355-100]
O. Keller, Aalborg Univ. (Denmark)

SESSION 1 FACILITIES AND THEIR OPTICS

- 7361 05 **Damage study for the design of the European XFEL beamline optics. (Invited Paper)**
[7361-04]
J. Gaudin, European XFEL (Germany) and Service des Accélérateurs, de Cryogénie et de Magnétisme, CEA (France); H. Sinn, L. Samoylova, F. Yang, T. Tschentscher, European XFEL (Germany)
- 7361 06 **The FERMI@Elettra FEL photon transport system (Invited Paper)** [7361-05]
D. Cocco, A. Abrami, A. Bianco, I. Cudin, C. Fava, D. Giuressi, R. Godnig, F. Parmigiani, L. Rumiz, R. Sergo, C. Svetina, M. Zangrando, Sincrotrone Trieste S.C.p.A. (Italy)

SESSION 2 DAMAGE BY ULTRA-SHORT XUV/X-RAY PULSES

- 7361 07 **Interaction of intense ultrashort XUV pulses with silicon** [7361-06]
R. Sobierajski, Institute of Physics (Poland) and FOM—Instituut voor Plasmafysica Rijnhuizen (Netherlands); D. Klinger, M. Jurek, J. B. Pełka, Institute of Physics (Poland); L. Juha, Institute of Physics (Czech Republic); J. Chalupský, Institute of Physics (Czech Republic) and Czech Technical Univ. (Czech Republic); J. Cihelka, V. Hajkova, L. Vysin, Institute of Physics (Czech Republic); U. Jastrow, N. Stojanovic, S. Toleikis, H. Wabnitz, HASYLAB/DESY (Germany); J. Krzywinski, SLAC National Accelerator Lab. (United States); S. Hau-Reige, R. London, Lawrence Livermore National Lab. (United States)

- 7361 08 **Response of molecular solids to ultra-intense femtosecond soft x-ray pulses** [7361-07]
 J. Chalupský, Institute of Physics (Czech Republic) and Czech Technical Univ. (Czech Republic); L. Juha, V. Hájková, J. Cihelka, Institute of Physics (Czech Republic); L. Vyšín, Institute of Physics (Czech Republic) and Czech Technical Univ. (Czech Republic); J. Gautier, Ecole Nationale Supérieure de Techniques Avancées (France); J. Hajdu, Uppsala Univ. (Sweden); S. P. Hau-Riege, Lawrence Livermore National Lab. (United States); M. Jurek, J. Krzywinski, Institute of Physics (Poland); R. A. London, Lawrence Livermore National Lab. (United States); E. Papalazarou, Ecole Nationale Supérieure de Techniques Avancées (France); J. B. Pelka, Institute of Physics (Poland); G. Rey, S. Sebban, Ecole Nationale Supérieure de Techniques Avancées (France); R. Sobierajski, Institute of Physics (Poland); N. Stojanovic, K. Tiedtke, S. Toilekis, T. Tschentscher, Deutsches Elektronen-Synchrotron (Germany); C. Valentin, Ecole Nationale Supérieure de Techniques Avancées (France); H. Wabnitz, Deutsches Elektronen-Synchrotron (Germany); P. Zeitoun, Ecole Nationale Supérieure de Techniques Avancées (France)
- 7361 0A **Efficient materials processing by dual action of XUV/Vis-NIR ultrashort laser pulses** [7361-09]
 K. Jakubczak, T. Mocek, J. Polan, P. Homer, B. Rus, Institute of Physics (Czech Republic); I. J. Kim, C. M. Kim, S. B. Park, T. K. Kim, G. H. Lee, C. H. Nam, Korea Advanced Institute of Science and Technology (Korea, Republic of); J. Chalupský, V. Hájková, L. Juha, Institute of Physics (Czech Republic); J. Sobota, T. Foršt, Institute of Scientific Instruments (Czech Republic)

SESSION 3 DAMAGE BY SHORT XUV/X-RAY PULSES

- 7361 0B **Silica nano-ablation using laser plasma soft x-rays (Invited Paper)** [7361-10]
 T. Makimura, S. Torii, Univ. of Tsukuba (Japan); H. Niino, National Institute of Advanced Industrial Science and Technology (Japan); K. Murakami, Univ. of Tsukuba (Japan)
- 7361 0C **Surface changes of solids under intense EUV irradiation using a laser-plasma source (Invited Paper)** [7361-11]
 A. Bartnik, H. Fiedorowicz, R. Jarocki, J. Kostecki, R. Rakowski, M. Szczurek, Military Univ. of Technology (Poland)
- 7361 0D **Direct structuring of solids by EUV radiation from a table-top laser produced plasma source (Invited Paper)** [7361-12]
 F. Barkusky, A. Bayer, C. Peth, K. Mann, Laser-Lab. Göttingen e.V. (Germany)

SESSION 4 THEORY AND COMPUTER SIMULATION

- 7361 0E **Dynamic of electronic subsystem of semiconductors excited with an ultrashort VUV laser pulse** [7361-13]
 N. Medvedev, B. Rethfeld, Technische Univ. of Kaiserslautern (Germany)
- 7361 0F **Radiation damage within atomic clusters irradiated with intense VUV radiation** [7361-14]
 B. Ziaja, H. Wabnitz, F. Wang, E. Weckert, Deutsches Elektronen-Synchrotron (Germany); T. Möller, Technische Univ. Berlin (Germany)

- 7361 OG **Modelling of damage processes of the optical-cryogenic sensor at microscopic and macroscopic levels** [7361-15]
V. Yatsenko, Institute of Space Research (Ukraine); L. Yatsenko, A. Negriyko, J. Potemkina, E. Udovitskaya, Institute of Physics (Ukraine)

SESSION 5 DAMAGE TO MULTILAYERS

- 7361 OI **Damage studies of multilayer optics for XUV free electron lasers (Invited Paper)** [7361-17]
E. Louis, A. R. Khorsand, FOM—Instituut voor Plasmafysica Rijnhuizen (Netherlands); R. Sobierajski, FOM—Instituut voor Plasmafysica Rijnhuizen (Netherlands) and Institute of Physics (Poland); E. D. van Hattum, FOM—Instituut voor Plasmafysica Rijnhuizen (Netherlands); M. Jurek, D. Klinger, J. B. Pelka, Institute of Physics (Poland); L. Juha, J. Chalupský, J. Cihelka, V. Hajkova, Institute of Physics (Czech Republic); U. Jastrow, S. Toleikis, H. Wabnitz, K. I. Tiedtke, Deutsches Elektronen-Synchrotron (Germany); J. Gaudin, European XFEL, Deutsches Elektronen-Synchrotron (Germany); E. M. Gullikson, Lawrence Berkeley National Lab. (United States); F. Bijkerk, FOM—Instituut voor Plasmafysica Rijnhuizen (Netherlands)
- 7361 OJ **Sub-micron focusing of soft x-ray free electron laser beam** [7361-18]
S. Bajt, Deutsches Elektronen-Synchrotron (Germany); H. N. Chapman, Univ. of Hamburg (Germany); A. J. Nelson, R. W. Lee, Lawrence Livermore National Lab. (United States); S. Toleikis, Deutsches Elektronen-Synchrotron (Germany); P. Mirkarimi, J. B. Alameda, S. L. Baker, H. Vollmer, R. T. Graff, Lawrence Livermore National Lab. (United States); A. Aquila, E. M. Gullikson, J. Meyer Ilse, Lawrence Berkeley National Lab. (United States); E. A. Spiller, Spiller X-ray Optics (United States); J. Krzywinski, Stanford Linear Accelerator Ctr. (United States); L. Juha, J. Chalupský, V. Hájková, Academy of Sciences (Czech Republic); J. Hajdu, Uppsala Univ. (Sweden); T. Tschentscher, Deutsches Elektronen-Synchrotron (Germany)
- 7361 OL **Competitive reactions of carbon deposition and oxidation on the surface of Mo/Si multilayer mirrors by EUV irradiation (Invited Paper)** [7361-20]
M. Niibe, K. Koida, Univ. of Hyogo (Japan)

SESSION 6 LASER-INDUCED DAMAGE

- 7361 OM **Laser damage densities measurements on fused silica optics: round-robin test at 351–355 nm** [7361-21]
L. Lamaignère, M. Loiseau, T. Donval, R. Courchinoux, S. Bouillet, J.-C. Poncetta, B. Bertussi, H. Bercegol, Commissariat à l'Énergie Atomique (France)
- 7361 ON **Laser-induced damage studies in optical elements using x-ray laser interferometric microscopy** [7361-22]
D. Margarone, M. Kozlová, J. Nejd, B. Rus, T. Mocek, P. Homer, J. Polan, M. Stupka, Institute of Physics (Czech Republic); G. Jameloł, K. Cassou, S. Kazamias, A. Klisnick, D. Ros, .LIXAM, CNRS, Univ. Paris-Sud (France); H. Bercegol, Commissariat à l'Énergie Atomique (France); C. Danson, S. Hawkes, Rutherford Appleton Lab. (United Kingdom)

- 7361 00 **Characterization of the focused beam of 10-Hz desktop capillary-discharge 46.9-nm laser** [7361-23]
L. Vyšín, T. Burian, J. Chalupský, Institute of Physics (Czech Republic) and Czech Technical Univ. in Prague (Czech Republic); M. Grisham, Colorado State Univ., Ft. Collins (United States); V. Hájková, Institute of Physics (Czech Republic); S. Heinbuch, Colorado State Univ. (United States); K. Jakubczak, Institute of Physics (Czech Republic); D. Martz, Colorado State Univ. (United States); T. Mocek, Institute of Physics (Czech Republic); P. Pira, Charles Univ. in Prague (Czech Republic); J. Polan, Institute of Physics (Czech Republic); J. J. Rocca, Colorado State Univ., Ft. Collins (United States); B. Rus, Institute of Physics (Czech Republic); J. Sobota, Institute of Scientific Instruments (Czech Republic); L. Juha, Institute of Physics (Czech Republic)

SESSION 7 LASER PLASMAS

- 7361 0P **Optical emission spectroscopy of various materials irradiated by soft x-ray free-electron laser** [7361-24]
J. Cihelka, Institute of Physics (Czech Republic) and J. Heyrovský Institute of Physical Chemistry (Czech Republic); L. Juha, Institute of Physics (Czech Republic); J. Chalupský, Institute of Physics (Czech Republic) and Czech Technical Univ. (Czech Republic); F. B. Rosmej, Univ. Pierre et Marie Curie (France); O. Renner, Institute of Physics (Czech Republic); K. Saksl, Institute of Materials Research SAS (Slovakia); V. Hájková, L. Vyšín, Institute of Physics (Czech Republic); E. Galtier, R. Schott, Univ. Pierre et Marie Curie (Slovakia); A. R. Khorsand, FOM— Instituut voor Plasmafysica Rijnhuizen (Netherlands); D. Riley, T. Dzelzainis, Queen's Univ. Belfast (United Kingdom); A. J. Nelson, R. W. Lee, Lawrence Livermore National Lab. (United States); P. A. Heimann, Lawrence Berkeley National Lab. (United States); B. Nagler, S. Vinko, J. Wark, T. Whitcher, Univ. of Oxford (United Kingdom); S. Toilekis, T. Tschentscher, R. Fäustlin, H. Wabnitz, S. Bajt, H. Chapman, Deutsches Elektronen-Synchrotron (Germany); J. Krzywinski, SLAC National Accelerator Lab. (United States); R. Sobierajski, D. Klinger, M. Jurek, J. Pelka, Institute of Physics (Poland); S. Hau-Riege, R. A. London, Lawrence Livermore National Lab. (United States); J. Kuba, Czech Technical Univ. in Prague (Czech Republic); N. Stojanovic, Deutsches Elektronen-Synchrotron (Germany); K. Sokolowski-Tinten, Univ. Duisburg-Essen (Germany); A. J. Gleeson, Science and Technology Facilities Council (United Kingdom); M. Störmer, GKSS-Forschungszentrum Geesthacht (Germany); J. Andreasson, J. Hajdu, B. Iwan, N. Timneanu, Uppsala Univ. (Sweden)
- 7361 0Q **Nonlinear 6-fold enhancement of laser drilling efficiency by double pulse mode: prospective in medicine application** [7361-26]
N. S. Pershina, S. M. Pershin, Prohorov General Physics Institute (Russian Federation); M. Cech, I. Prochazka, Czech Technical Univ. in Prague (Czech Republic)

SESSION 8 DAMAGE TO PHOSPHORS, FILTERS, DETECTORS AND COATINGS

- 7361 0R **Phosphor materials under high-density XUV FEL excitation: mechanisms of luminescence quenching** [7361-27]
S. Vielhauer, V. Babin, Univ. of Tartu (Estonia); M. De Grazia, Commissariat à l'Energie Atomique (France); E. Feldbach, M. Kirm, V. Nagirnyi, Univ. of Tartu (Estonia); A. N. Vasil'ev, Moscow State Univ. (Russian Federation)

- 7361 OS **Factors affecting the transmission and stability in complex fluorides in VUV spectral region** [7361-28]
M. Nikl, Institute of Physics (Czech Republic); H. Sato, Fukuda X'tal Lab. (Japan);
E. Mihokova, Institute of Physics (Czech Republic); T. Mabuchi, T. Nawata, Tokuyama Co.
Ltd. (Japan); A. Yoshikawa, Tohoku Univ. (Japan); J. Pejchal, Institute of Physics (Japan) and
Tohoku Univ. (Japan); N. Kawaguchi, S. Ishizu, K. Fukuda, T. Suyama, Tokuyama Co. Ltd.
(Japan)
- 7361 OT **Radiation hardness of Al_xGa_{1-x}N photodetectors exposed to Extreme UltraViolet (EUV) light beam** [7361-29]
P. E. Malinowski, Interuniversity MicroElectronic Ctr. (Belgium) and Katholieke Univ. Leuven
(Belgium); J. John, Interuniversity MicroElectronic Ctr. (Belgium); F. Barkusky, Laser-Lab.
Göttingen e.V. (Germany); J. Y. Duboz, CRHEA, CNRS, (France); A. Lorenz, Interuniversity
MicroElectronic Ctr. (Belgium) and Katholieke Univ. Leuven (Belgium); K. Cheng, J. Derluyn,
M. Germain, P. De Moor, K. Minoglou, Interuniversity MicroElectronic Ctr. (Belgium); A. Bayer,
K. Mann, Laser-Lab. Göttingen e.V. (Germany); J.-F. Hochedez, B. Giordanengo, Royal
Observatory of Belgium (Belgium); G. Borghs, R. Mertens, Interuniversity MicroElectronic Ctr.
(Belgium) and Katholieke Univ. Leuven (Belgium)
- 7361 OU **Morphology, microstructure, stress and damage properties of thin film coatings for the LCLS x-ray mirrors** [7361-30]
R. Soufli, S. L. Baker, J. C. Robinson, Lawrence Livermore National Lab. (United States);
E. M. Gullikson, Lawrence Berkeley National Lab. (United States); T. J. McCarville,
M. J. Pivovarov, Lawrence Livermore National Lab. (United States); P. Stefan, SLAC National
Accelerator Lab. (United States); S. P. Hau-Riege, R. Bionta, Lawrence Livermore National
Lab. (United States)

SESSION 9 POSTER SESSION

- 7361 OV **Degradation of thin-film filters irradiated by debris emission of a laser induced plasma** [7361-31]
D. Schäfer, Univ. of Applied Sciences Koblenz (Germany); U. Wiesemann, ACCEL Instruments
GmbH (Germany); T. Nisius, T. Wilhein, Univ. of Applied Sciences Koblenz (Germany)
- 7361 OW **Risk analysis of laser elements for complex characterization of damages by space radiation** [7361-32]
M. Brodyn, V. Bezrodnyi, A. Negriyko, Institute of Space Research (Ukraine); V. Yatsenko,
Institute of Physics (Ukraine)
- 7361 OX **Characterization of tin vapor from CO₂ laser produced EUV light source** [7361-33]
Y. Ueno, T. Yanagida, T. Sukanuma, H. Komori, A. Sumitani, A. Endo, EUVA (Japan)
- 7361 OY **Applicability of transmissive diffractive optics to high flux FEL radiation** [7361-34]
T. Nisius, R. Fröhe, D. Schäfer, Univ. of Applied Sciences Koblenz (Germany); M. Wieland, Univ.
Hamburg (Germany); T. Wilhein, Univ. of Applied Sciences Koblenz (Germany)
- 7361 OZ **Toward a better understanding of multi-wavelength effects on KDP crystals** [7361-36]
S. Reyné, M. Loiseau, CEA/CESTA (France); G. Duchateau, CEA/Le Ripault (France);
J.-Y. Natoli, Institut Fresnel, CNRS (France); L. Lamaignère, CEA/CESTA (France)

- 7361 10 **Damage thresholds of various materials irradiated by 100-ps pulses of 21.2-nm laser radiation** [7361-37]
V. Hájková, Institute of Physics (Czech Republic); J. Chalupský, Institute of Physics (Czech Republic) and Czech Technical Univ. (Czech Republic); H. Wabnitz, J. Feldhaus, Deutsches Elektronen-Synchrotron (Germany); M. Störmer, GKSS Research Ctr. (Germany); Ch. Hecquet, Institut d'Optique, CNRS, Univ. Paris-Sud (France); T. Mocek, M. Kozlová, J. Polan, P. Homer, B. Rus, L. Juha, Institute of Physics (Czech Republic)
- 7361 12 **Applications of compact laser-driven EUV/XUV plasma sources** [7361-39]
F. Barkusky, A. Bayer, S. Döring, B. Flöter, P. Großmann, C. Peth, M. Reese, K. Mann, Laser-Lab. Göttingen e.V. (Germany)
- 7361 13 **XUV metrology: surface analysis with extreme ultraviolet radiation** [7361-40]
M. Banyay, L. Juschkin, T. Bücke, P. Loosen, RWTH Aachen (Germany); A. Bayer, F. Barkusky, S. Döring, C. Peth, K. Mann, Laser-Lab. Göttingen e.V. (Germany); H. Blaschke, I. Balasa, D. Ristau, Laser Zentrum Hannover e.V. (Germany)

Author Index

Conference Committee

Symposium Chairs

Pavel Tomanek, Brno University of Technology (Czech Republic)
Alan Michette, King's College London (United Kingdom)
Bahaa Saleh, Boston University (United States)

Symposium Honorary Chair

Jan Perina, Sr., Palacký University (Czech Republic)

Conference Chairs

Libor Juha, Institute of Physics (Czech Republic)
Saša Bajt, Deutsches Elektronen-Synchrotron (Germany)
Ryszard Sobierajski, Institute of Physics (Poland) and FOM—Instituut voor Plasmafysica Rijnhuizen (Netherlands)

Program Committee

Fred Bijkerk, FOM-Instituut voor Plasmafysica Rijnhuizen (Netherlands)
Henryk Fiedorowicz, Institute of Electrooptics, WAT (Poland)
Jérôme Gaudin, European XFEL (Germany)
Jacek Krzywinski, Stanford Linear Accelerator Center (United States)
Richard London, Lawrence Livermore National Laboratory (United States)
Klaus Mann, Laser-Laboratory Göttingen e.V. (Germany)
Tomáš Mocek, Institute of Physics (Czech Republic)
Ladislav Pina, Czech Technical University in Prague (Czech Republic)
Jorge J. Rocca, Colorado State University (United States)
Michael Störmer, GKSS-Forschungszentrum Geesthacht, GmbH (Germany)
Philippe Zeitoun, Ecole Nationale Supérieure de Techniques Avancées (France)
Beata Ziaja-Motyka, Deutsches Elektronen-Synchrotron (Germany)

Session Chairs

- 1 Facilities and their Optics
Libor Juha, Institute of Physics (Czech Republic)
- 2 Damage by Ultra-short XUV/X-ray Pulses
Eric Louis, FOM—Instituut voor Plasmafysica Rijnhuizen (Netherlands)

- 3 Damage by Short XUV/X-ray Pulses
Jérôme Gaudin, European XFEL (Germany)
- 4 Theory and Computer Simulation
Saša Bajt, Deutsches Elektronen-Synchrotron (Germany)
- 5 Damage to Multilayers
Ryszard Sobierajski, Institute of Physics (Poland) and FOM-Instituut voor
Plasmafysica Rijnhuizen (Netherlands)
- 6 Laser-induced Damage
Jaromír Chalupský, Institute of Physics (Czech Republic)
- 7 Laser Plasmas
Beata Ziaja-Motyka, Deutsches Elektronen-Synchrotron (Germany)
- 8 Damage to Phosphors, Filters, Detectors and Coatings
Kai I. Tiedtke, Deutsches Elektronen-Synchrotron (Germany)
Elke Ploenjes, Deutsches Elektronen-Synchrotron (Germany)

Introduction

Damage to VUV, EUV and X-ray Optics II (XDam2) Conference (held every two years in Prague) focuses on studies of damage to optical elements irradiated by high average and/or high peak fluxes of high-energy photons, i.e., VUV/EUV radiation and x-rays. The number of participants is growing, showing that this is a lively and very active research area.

Irreversible changes in various materials induced by high fluxes of EUV/x-ray photons were first studied more than twenty-five years ago (for a review of early studies see [1]). However, it is only in the last decade that this type of research became very active, primarily due to the development of new, intense EUV and x-ray sources.

Systematic studies in this field are driven by different goals and interests:

- 1) estimating and minimizing damage to surfaces of highly irradiated EUV/x-ray optical elements for the guiding and focusing of short-wavelength laser beams as well as those used for long-term irradiation with high repetition rate sources,
- 2) durability assessments of materials suggested for the first walls of ICF reactors and optical elements exposed to intense UV/x-ray radiation in a laser-plasma interaction chambers,
- 3) diffraction-limited ultra-structuring and patterning of solid surfaces for fabrication of microelectronic and micromechanical elements and devices,
- 4) determination of radiation field characteristics: imaging of spatial radiation energy distribution in a focused beam imprinted on the irradiated material and determination of pulse energy content,
- 5) production of very dense plasma with low electron temperatures, i.e. $kT_e \sim 10$ eV, which is often called WDM—Warm Dense Matter.

Although this conference is primarily focused on damage to surfaces of highly irradiated EUV/x-ray optical elements and the effect of long-term irradiation with high repetition rate sources, we believe the results presented here will also be of interest to researchers working in other areas listed above.

The EUV/x-ray sources used for material modification emit at both low peak power (synchrotron radiation and rotating anode sources) and high peak power (free-electron lasers - FELs and various sources based on hot dense plasmas).

The short-wavelength FEL facilities (FLASH [2], LCLS [3], European XFEL, FERMI@Elettra, SCSS, Japanese XFEL) and their optics were introduced and discussed in details in the first part of this conference. These were followed by several contributions about laboratory-scaled sources utilizing collection and focusing of EUV/x-ray radiation emitted from laser-produced plasmas. These sources provide long EUV/x-ray pulses as compared to FEL facilities, are very handy, and their operation is economical. Thus, they represent a work-horse in the rapidly growing area of UV/x-ray-induced nano-structuring and surface modification.

With low-peak-power sources, materials are primarily removed by photo-induced desorption of material components from the irradiated sample surface. Each EUV/x-ray photon carries enough energy to break any chemical bond. This energy is usually also higher than the cohesive energy of any crystal. Therefore the photons absorbed in a near-surface region may create small fragments of a sample material, which are emitted into the vacuum. It is necessary to underline, that in the case of low-peak-intensity irradiation, material is removed only from the surface and a very thin near-surface layer.

The situation is quite different when the sample is exposed to a high-peak-power source that delivers energy in individual, high-energy pulses. The sample is then exposed to a high local dose of radiation (given by the energy content of the pulse and the absorption length of the radiation in the irradiated material) in a short period of time (given by the pulse duration), i.e. at a very high dose rate. This means that a large number of events that cause radiation-induced structural decomposition (i.e., polymer chain scissions, etc.), occurs almost simultaneously in a relatively thick layer of irradiated material. Since a portion of the radiation energy absorbed in the material will be thermalized, the sudden heating of the layer, which is also heavily chemically altered by the radiation, must be taken into account. The overheated, fragmented region of the sample represents a new phase, which tends to blow off into the vacuum. These particular processes, as well as specific features of short-wavelength ablation with respect to ablation induced by conventional UV-Vis-IR sources, represent the subject of interest of numerous research groups.

Results of extensive investigations in both above-mentioned modes have been reported at the conference in various materials (e.g., elemental semiconductors, aluminum foils, molecular solids) and composed systems (e.g., single thin layers deposited on a massive substrate, multilayers, phase zone plates). In addition to that, the intermediate region between the desorption and the ablation was indicated and demonstrated. Experiments with the tightly focused FLASH beam gave a unique chance to observe all three phenomena appearing together on the surface of a crater created by a single FEL shot.

Although most of participants reported desorption and ablation of irradiated material, i.e., photo-induced erosion, several contributions presented at the conference were dealing with an expansion of irradiated material or carbonaceous solids deposition on irradiated surfaces. The surface contamination of EUV/x-ray optics by radiation-induced carbon deposits and protection against the damage of this kind is of interest from scientific and technological perspective [4].

With soon-be-operational x-ray FELs the interest is shifting towards the short-wavelength region (~ keV) and ultra-high intensities (micro-focusing issues). This is also bringing challenges for the theory and computer modeling of radiation damage.

References

I. L. Juha et al., "Ablation of poly(methyl methacrylate) by a single pulse of soft x-rays emitted from Z-pinch and laser-produced plasmas," *Surf. Rev. Lett.* 9, 347 (2002); "Short-wavelength ablation of molecular solids: pulse duration and wavelength effects," *J. Microlith. Microfab. Microsyst.* 4, 033007 (2005).

2. K. Tiedtke et al., "The soft x-ray free-electron laser FLASH at DESY: beamlines, diagnostics and end-stations," *New J. Phys.* 11, 023029 (2009).
3. J. D. Bozek, "AMO instrumentation for the LCLS x-ray FEL," *Eur. J. Phys., Spec. Topics* 169, 129 (2009).
4. S. Bajt, N. V. Edwards, T. E. Madey, "Properties of ultrathin films appropriate for optics capping layers exposed to high energy photon irradiation," *Surf. Sci. Rev.* 63, 73 (2008).

Libor Juha
Saša Bajt
Ryszard Sobierajski

