EUV Sources for Lithography
EUV Sources
for Lithography

Vivek Bakshi
I dedicate this book to my parents, wife, and daughter
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*Kevin Kemp*  

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Preface

Until recently, EUV source power was the number one challenge to implementing EUV lithography (EUVL) in the high-volume manufacturing of computer chips. But due to the dedicated efforts of a few dozen research groups around the world, EUV source technology continues to advance. Today, with tremendous improvements in source power and other characteristics, source power is no longer the leading challenge. EUV sources have evolved from a laboratory concept to reality, with alpha-level EUV sources being delivered for integration in alpha-level EUV scanners.

This reference book contains 38 chapters contributed by leading researchers and suppliers in the field of EUV sources for EUVL. The chapter topics are intended to cover the needs of practitioners of the technology as well as readers who want an introduction to EUV sources. The book begins with in-depth coverage of EUV source requirements and the status of the technology, followed by a review of fundamental atomic data and descriptions of theoretical models of discharge-produced plasma (DPP) and laser-produced plasma (LPP) based EUV sources, prominent DPP and LPP designs, and alternative technologies for producing EUV radiation. Also covered are topics in EUV source metrology, EUV source components (collectors, electrodes), debris mitigation, and mechanisms of component erosion in EUV sources.

As EUV source technology has progressed, researchers and commercial suppliers around the world have published more than 100 papers per year, and the amount of technical data on EUV source technology continues to increase. My effort as volume editor has been to produce an authoritative reference book on EUV source technology, which has not existed until now. In the future one may need to consult the proceedings of SEMATECH’s EUV Source Workshops and SPIE’s Microlithography conference for the most recent performance improvements in EUV sources, but this text will still deliver the in-depth technical background information on particular technical approaches and on EUV source technology in general.

The primary strength of this book is that the contributions came from leading experts. The choice of having many authors per section has produced a comprehensive and true reference book, covering a range of technical options and opinions. I have done my best to make each chapter a complete reference in itself, though some sections—usually the introductory sections of chapters—inevitably overlap. For example, although each chapter mentions the requirements for a source, the
reader is encouraged to consult Chapter 2 to understand the details of EUV source requirements. Likewise, many authors refer to certain issues such as debris generation in their chapters; however, the reader is directed to Chapter 37 for a comprehensive reading on the fundamentals of debris generation and mitigation.

This project has been successful due to the dedication and hard work of many technologists worldwide. Therefore, I would like to acknowledge and thank the authors who have worked very hard to produce a reference chapter on their technical work. Their quality manuscripts made my job as an editor much easier. This book is essentially the fruit of their labor.

I would like to thank my colleagues at SEMATECH’s member companies, as well as the authors in this volume who took the time to review the chapters by their colleagues. I would especially like to thank some of the referees who reviewed multiple chapters: Vadim Banine, Vladimir Borisov, Peter Choi, Akira Endo, Igor Fomenkov, Samir Ellwi, Björn Hansson, Ahmed Hassanein, Lennie Klebanoff, Konstantin Koshelev, Thomas Krücken, Hans J. Kunze, Rainer Lebert, Malcolm McGeoch, Katsunobu Nishihara, Gerry O’Sullivan, Joseph Pankert, Martin Richardson, David Ruzic, Uwe Stamm, Yusuke Teramoto, and Sergey Zakharov.

I would also like to acknowledge the contributions of my family, whose influence, encouragement, and support have allowed me to undertake such a project. First of all, my father, Mr. Om Prakash Bakshi, MA, set a very high standard for written communication and the pursuit of excellence, which still today I can only strive to meet. My mother, Mrs. Pushpa Bakshi, MA, retired lecturer of the Punjabi language, always set the example of hard work and taught me a pragmatic approach toward solving everyday problems, which still guides me. My wife, Laura Coyle, encouraged me to undertake this intellectual pursuit and has always been an example of innovation and uncompromising attention to quality and detail for achieving perfection, as evident in her own achievements. Laura’s and my daughter Emily’s encouragement have allowed me to continue and complete this project. For these reasons, I have dedicated this book to my parents and my wife and daughter.

I would like to thank SPIE acquisitions editor Timothy Lamkins, with whom I worked to generate the concept of this book. I would also like to thank SPIE editor Margaret Thayer, who made one of the largest book projects ever undertaken by SPIE Press a very smooth process. I very much appreciate her support and hard work for making this book project a reality.

Finally, I would like to thank my former manager, Kevin Kemp, for his guidance and support in this project, and my employer, SEMATECH, which exemplifies industry cooperation in the semiconductor community. SEMATECH has created a global platform to facilitate consensus on the direction of technology and to promote cooperative work in the pre-competitive arena of computer chip manufacturing. Hopefully, this book will set an example of how a large number of experts and competitors can cooperate to produce a reference work to benefit an entire industry.

Vivek Bakshi
December 2005
Introduction

In semiconductor manufacturing, progress is measured in terms of the industry’s continued ability to adhere to Moore’s Law, which states that the number of transistors on a chip doubles about every two years. The *International Technology Roadmap for Semiconductors* (ITRS) dictates expected performance specifications for chip manufacturing technology to ensure continued adherence to this law. Accomplishing these specifications in turn requires the development and perfection of new technologies at a pace that is unmatched by any other industry. No single company can hope to do this alone: The increasing complexity of the technical challenges and the rising cost of development call for an unprecedented level of resource and risk sharing among semiconductor manufacturers, tool and materials suppliers, and research institutions and consortia.

Among the technical challenges facing the semiconductor industry, lithography presents some of the most formidable problems, particularly the search for a next-generation lithography solution that can provide for high-volume manufacturing of computer chips at the 32 nm node and beyond. Extreme ultraviolet lithography (EUVL) is the leading candidate to succeed optical lithography at the currently used wavelength of 193 nm. However, the technical challenges of source power, source component and optics lifetime, resist performance, and mask defectivity still must be addressed to ensure the cost-effective and timely implementation of EUVL. Furthermore, the industry infrastructure in these key areas needs to be developed rapidly to support planned manufacturing at the 32 nm generation.

Source power and associated source component lifetime are among the most critical of all the EUVL challenges. The amount of available source power translates directly to the wafer throughput that can be achieved by an EUV exposure tool. Source component lifetime affects the cost of maintaining the tool, including the amount of time that a tool must be taken out of productive service for maintenance. Both these factors in turn drive the per-wafer processing cost for the technology. The past four to six years have seen a concerted effort on the part of suppliers and researchers to achieve the power levels and component lifetimes required to produce commercial EUV sources for lithographic applications. This volume celebrates the successes along this path and provides a reference for practitioners in the field and other interested readers.

SEMATECH is a consortium of the world’s leading semiconductor manufacturers, and is a powerful catalyst for accelerating the commercialization of technology
innovations into manufacturing solutions for the semiconductor industry. Its lithography division conducts targeted research projects to accelerate technology and infrastructure development to meet the lithography requirements of the ITRS. It also organizes numerous technical workshops and symposia involving technologists and decision-makers from around the world to foster global, pre-competitive cooperation and to drive consensus solutions for future semiconductor manufacturing technology. Continued progress in the development of EUVL is a prime example of SEMATECH’s efforts in this regard, and this book is a direct result of such collaboration.

Kevin Kemp
Director, Lithography Division
SEMATECH
List of Contributors

J. P. Allain
Argonne National Laboratory, USA
Moza Al-Rabban
Qatar University, Qatar
University of Central Florida, USA
Richard J. Anderson
Sandia National Laboratories, USA
Željko Andreič
University of Zagreb, Croatia
Rolf Apetz
Philips Extreme UV GmbH, Germany
Thierry Auguste
EXULITE Project
DSM/DRECAM/SPAM, CEA, France
Saša Bajt
Lawrence Livermore National Laboratory (LLNL), USA
Vivek Bakshi
SEMAPTECH, USA
William P. Ballard
Sandia National Laboratories, USA
Vadim Banine
ASML, The Netherlands
Benoit Barthod
EXULITE Project
DSM/DRECAM/SPAM, CEA, France
Eric C. Benck
National Institute of Standards and Technology, USA
Klaus Bergmann
Fraunhofer Institut für Lasertechnik, Germany
Fred Bijkerk
FOM-Institute for Plasma Physics Rijnhuizen, The Netherlands
Thomas Blenski
DSM/DRECAM/SPAM, CEA-Saclay, France
Vladimir M. Borisov
Troitsk Institute of Innovation and Fusion Research (TRINITI), Russia
Norbert R. Böwering
Cymer, Inc., USA
J. N. Brooks
Argonne National Laboratory, USA
Michael Brownell
Powerlase Ltd., UK
Caspar Bruineman
Scientec Engineering, The Netherlands
Dean A. Buchenauer
Sandia National Laboratories, USA
T. Burtseva
Argonne National Laboratory, USA
Tibério Ceccotti  
EXULITE Project  
DSM/DRECAM/SPAM, CEA, France

Guy Cheymol  
EXULITE Project  
DSM/DRECAM/SPAM, CEA, France

Boris N. Chichkov  
Laser Zentrum Hannover e.V., Germany

Peter Choi  
EPPRA sas, France

S. S. Churilov  
Institute for Spectroscopy Russian Academy of Sciences, Russia

Andrew J. Comley  
Powerlase Ltd., UK

Philippe Cormont  
EXULITE Project  
DSM/DRECAM/SPAM, CEA, France

Anthony Cummings  
University College Dublin, Ireland

René de Bruijn  
XTREME technologies, Germany

Andrey I. Demin  
Troitsk Institute of Innovation and Fusion Research (TRINITI), Russia

Günther Derra  
Philips GmbH Research Laboratories and Philips Extreme UV GmbH, Germany

Padraig Dunne  
University College Dublin, Ireland

André Egbert  
phoenix|euv Systems + Services GmbH, Germany

Wilhelm Egle  
Carl Zeiss Laser Optics GmbH, Germany

Samir Ellwi  
Powerlase Ltd., UK

Alexander V. Eltsov  
Troitsk Institute of Innovation and Fusion Research (TRINITI), Russia

Akira Endo  
EUVL System Development Association (EUVA), Japan

Igor V. Fomenkov  
Cymer, Inc., USA

Steven Fornaca  
Northrop Grumman Corporation, USA

Neal R. Fornaciari  
Sandia National Laboratories, USA

Hans Franken  
ASML, The Netherlands

Kai Gäbel  
XTREME technologies, Germany

R. Gayazov  
Institute for Spectroscopy Russian Academy of Sciences, Russia

Simi George  
University of Central Florida, USA

John D. Gillaspy  
National Institute of Standards and Technology (NIST), USA

Franck Gilleron  
CEA/DIF, France

John E. M. Goldsmith  
Sandia National Laboratories, USA
V. Gomozov
Institute for Spectroscopy Russian Academy of Sciences, Russia

Steve Grantham
National Institute of Standards and Technology (NIST), USA

Björn A. M. Hansson
Royal Institute of Technology, Sweden

Jeffrey Hartlove
Northrop Grumman Corporation, USA

A. Hassanein
Argonne National Laboratory, USA

Patrick Hayden
University College Dublin, Ireland

Jean-François Hergott
EXULITE Project
DSM/DRECAM/SPAM, CEA, France

Hans M. Hertz
Royal Institute of Technology, Sweden

Jerzy R. Hoffman
Cymer, Inc., USA

Robert Huiting
FOM-Institute for Plasma Physics Rijnhuizen, The Netherlands

Z. Insepov
Argonne National Laboratory, USA

Alexander S. Ivanov
Troitsk Institute of Innovation and Fusion Research (TRINITI), Russia

V. V. Ivanov
Institute for Spectroscopy Russian Academy of Sciences, Russia

Lawrence Iwaki
Northrop Grumman Corporation, USA

Jeroen Jonkers
Philips Extreme UV GmbH, Germany

Christian Keyser
Naval Research Laboratories, USA

Oleg V. Khodykin
Cymer, Inc., USA

Oleg B. Kristoforov
Troitsk Institute of Innovation and Fusion Research (TRINITI), Russia

Yuriy B. Kiryukhin
Troitsk Institute of Innovation and Fusion Research (TRINITI), Russia

Leonard E. Klebanoff
Sandia National Laboratories, USA

Jürgen Klein
Fraunhofer Institut für Lasertechnik, Germany

Jürgen Kleinschmidt
XTREME technologies, Germany

Chiew-Seng Koay
University of Central Florida, USA

V. G. Koloshnikov
Institute for Spectroscopy Russian Academy of Sciences, Russia

Hiroshi Komori
EUVL System Development Association (EUV A), Japan

I. Konkashbaev
Argonne National Laboratory, USA

E. D. Korop
Institute for Spectroscopy Russian Academy of Sciences, Russia

K. N. Koshelev
Institute for Spectroscopy Russian Academy of Sciences, Russia
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<tr>
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<th>Location</th>
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<td>V. Krivtsov</td>
<td>Institute for Spectroscopy Russian Academy of Sciences, Russia</td>
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<td>Thomas Krücken</td>
<td>Philips Research Laboratories, Germany</td>
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<td>H.-J. Kunze</td>
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<td>Rainer Lebert</td>
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<td>Michael Loeken</td>
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<td>Thomas Lucatorto</td>
<td>National Institute of Standards and Technology (NIST), USA</td>
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<td>Alastair A. MacDowell</td>
<td>Lawrence Berkeley National Laboratory (LBNL), USA</td>
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<td>Piotr Marczuk</td>
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<td>Armando Martos</td>
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<td>R. D. McGregor</td>
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<td>Luke McKinney</td>
<td>University College Dublin, Ireland</td>
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Kazuya Ota  
Nikon Corporation, Japan

Joseph Pankert  
Philips Extreme UV GmbH, Germany

William N. Partlo  
Cymer, Inc., USA

Michael Petach  
Northrop Grumman Corporation, USA

Michel Poirier  
DSM/DRECAM/SPAM, CEA-Saclay, France

Samuel Ponti  
Northrop Grumman Corporation, USA

Joshua M. Pomeroy  
National Institute of Standards and Technology (NIST), USA

Sven Probst  
Fraunhofer Institut für Lasertechnik, Germany

Alexander V. Prokofiev  
Troitsk Institute of Innovation and Fusion Research (TRINITI), Russia

Laura P. Ratliff  
National Institute of Standards and Technology (NIST), USA

Curtis L. Rettig  
Cymer, Inc., USA

B. Rice  
Intel Corporation, USA

Martin Richardson  
University of Central Florida, USA

Oliver Rosier  
Fraunhofer Institut für Lasertechnik, Germany

David N. Ruzic  
University of Illinois at Urbana-Champaign, USA

A. N. Ryabtsev  
Institute for Spectroscopy Russian Academy of Sciences, Russia

V. Safronov  
Troitsk Institute for Innovation and Fusion Research (TRINITI), Russia

Akira Sasaki  
Advanced Photon Research Center, Japan

Hiroto Sato  
EUVL System Development Association (EUVA), Japan

Martin Schmidt  
EXULITE Project DSM/DRECAM/SPAM, CEA, France

Frank Scholze  
PTB, X-ray Radiometry Department, Germany

Guido Schriever  
XTREME technologies, Germany

Howard Scott  
Lawrence Livermore National Laboratory (LLNL), USA

Stefan Seiwerdt  
Fraunhofer Institut für Lasertechnik, Germany

Harry Shields  
Northrop Grumman Corporation, USA

Yu. V. Sidelnikov  
Institute for Spectroscopy Russian Academy of Sciences, Russia

Guido Siemons  
Philips Extreme UV GmbH, Germany
Wolfgang Singer  
Carl Zeiss SMT AG, Germany

T. Sizyuk  
Argonne National Laboratory, USA

V. Sizyuk  
Argonne National Laboratory, USA

Jacky Skrzypczak  
EXULITE Project  
DSM/DRECAM/SPAM, CEA, France

Christopher Smith  
Fraunhofer Institut für Lasertechnik, Germany

Uwe Stamm  
XTREME technologies, Germany

Randall St. Pierre  
Northrop Grumman Corporation, USA

Remko Stuik  
Leiden Observatory University of Leiden, The Netherlands

Olivier Sublemontier  
EXULITE Project  
DSM/DRECAM/SPAM, CEA, France

Atsushi Sunahara  
Institute for Laser Technology, Japan

Kazutoshi Takenoshita  
University of Central Florida, USA

Charles Tarrio  
National Institute of Standards and Technology (NIST), USA

Yusuke Teramoto  
EUVL System Development Association (EUVA), Japan

Mark Thomas  
Northrop Grumman Corporation, USA

Pierre-Yves Thro  
EXULITE Project  
DSM/DRECAM/SPAM, CEA, France

V. Tolkach  
Argonne National Laboratory, USA

I. Yu. Tolstikhina  
P. N. Lebedev Physical Institute  
Russian Academy of Sciences, Russia

Gerhard Ulm  
PTB, X-ray Radiometry Department, Germany

Santi Alonso van der Westen  
FOM-Institute for Plasma Physics  
Rijnhuizen, The Netherlands

Dominik Vaudrevange  
Philips Extreme UV GmbH, Germany

Robert Vest  
National Institute of Standards and Technology (NIST), USA

Armando Villarreal  
Northrop Grumman Corporation, USA

Alexander Yu. Vinokhodov  
Troitsk Institute of Innovation and Fusion Research (TRINITI), Russia

Vladimir A. Vodchits  
Troitsk Institute of Innovation and Fusion Research (TRINITI), Russia

Yutaka Watanabe  
Canon Inc., Japan

Rolf Wester  
Fraunhofer Institut für Lasertechnik, Germany

John White  
University College Dublin, Ireland

Obert R. Wood, II  
SEMATECH, USA
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<td>Sergey V. Zakharov</td>
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<td>RRC Kurchatov Institute, Russia</td>
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<td>Peter Zink</td>
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<td>G. G. Zukanishvili</td>
<td>Institute for Spectroscopy Russian Academy of Sciences, Russia</td>
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List of Abbreviations

AA average atom
ACR absolute cryogenic radiometer
ADM angular distribution monitor
AEM Auger electron microscopy
AES Auger electron spectroscopy
AFM atomic force microscopy
AIM aerial-image microscope
ALS Advanced Light Source (U.S.)
ANL Argonne National Laboratory (U.S.)
AO acousto-optical
arb. arbitrary
ASD axially symmetrical discharge
a.u. arbitrary units
BCA binary collision approximation
BW bandwidth
CBM carbon-based materials
CBS collision-based spectroscopy
CCD charge-coupled device
CE conversion efficiency
CES charged-exchange spectroscopy
CF ConFlat
CFC carbon-fiber composite
CI configuration interaction
CM collisional mixing
CO condenser optic
CoO cost of ownership
COR condenser-optic region
CR collisional radiative
CRE collisional radiative equilibrium
CRM collisional radiative mode
CTE coefficient of thermal expansion
cw continuous wave
CXRO Center for X-ray Optics (at LBNL, U.S.)
DCA direct configuration accounting
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<th>Abbreviation</th>
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<td>DCU</td>
<td>dual-crystal unit</td>
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<tr>
<td>DF</td>
<td>Dirac-Fock</td>
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<tr>
<td>DL</td>
<td>diffraction limit</td>
</tr>
<tr>
<td>DLC</td>
<td>diamondlike carbon</td>
</tr>
<tr>
<td>DMD</td>
<td>defect-mediated desorption</td>
</tr>
<tr>
<td>DPF</td>
<td>dense plasma focus</td>
</tr>
<tr>
<td>DPP</td>
<td>discharge-produced plasma</td>
</tr>
<tr>
<td>DPSS</td>
<td>diode-pumped solid state</td>
</tr>
<tr>
<td>DRT</td>
<td>discrete-ordinate method</td>
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<td>DTA</td>
<td>detailed term accounting</td>
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<td>DUV</td>
<td>deep ultraviolet</td>
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<td>DWA</td>
<td>distorted-wave approximation</td>
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<td>EBIT</td>
<td>electron-beam ion trap</td>
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<tr>
<td>EDX</td>
<td>energy dispersive x-ray spectroscopy</td>
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<td>EM</td>
<td>electromagnetic</td>
</tr>
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<td>EO</td>
<td>electro optical</td>
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<td>EOS</td>
<td>equation of state</td>
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<td>ES</td>
<td>electrostatic analyzer</td>
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<tr>
<td>ESA</td>
<td>spherical-sector electrostatic energy analyzer</td>
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<tr>
<td>ESIEA</td>
<td>electrostatic ion energy analyzer</td>
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<tr>
<td>ESR</td>
<td>electrical substitution radiometer</td>
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<td>ETS</td>
<td>Engineering Test Stand</td>
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<td>EUV</td>
<td>extreme ultraviolet</td>
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<td>EUVL</td>
<td>extreme ultraviolet lithography</td>
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<td>EUV LLC</td>
<td>EUV Limited Liability Corporation</td>
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<td>FAC</td>
<td>Flexible Atomic Code</td>
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<tr>
<td>FC</td>
<td>Flying Circus</td>
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<td>FDWG</td>
<td>Fundamental Data Working Group (of SEMATECH)</td>
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<td>FFS</td>
<td>flat-field spectrograph</td>
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<td>FMEA</td>
<td>failure-mode and effect analysis</td>
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<td>FOM</td>
<td>Fundamenteel Onderzoek der Materie (The Netherlands)</td>
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<td>FT</td>
<td>foil trap</td>
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<tr>
<td>FWHM</td>
<td>full width at half maximum</td>
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<td>GA</td>
<td>Gibbsian adsorption</td>
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<td>GDPP</td>
<td>gas-discharge produced plasma</td>
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<td>GEA</td>
<td>gridded energy analyzer</td>
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<td>GIM</td>
<td>grazing-incidence mirror</td>
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<td>HCI</td>
<td>highly charged ions</td>
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<td>HCT</td>
<td>hollow-cathode triggered</td>
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<td>HEDP</td>
<td>high-energy-density physics</td>
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<td>HEW</td>
<td>half energy width</td>
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<td>HF</td>
<td>Hartree-Fock</td>
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<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>HFR</td>
<td>Hartree-Fock approximation with relativistic extensions</td>
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<td>HFS</td>
<td>Hartree-Fock-Slater</td>
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<td>HLI</td>
<td>Helmholtz-Lagrange invariant</td>
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<td>HULLAC</td>
<td>Hebrew University Lawrence Livermore Atomic Code</td>
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<td>HV</td>
<td>high voltage</td>
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<td>HVE</td>
<td>high-voltage electrode</td>
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<td>HVM</td>
<td>high-volume manufacturing</td>
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<td>IBA</td>
<td>inverse bremsstrahlung absorption</td>
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<tr>
<td>IC</td>
<td>integrated circuit</td>
</tr>
<tr>
<td>ICE</td>
<td>intrinsic conversion efficiency</td>
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<td>IDEA</td>
<td>interferometric data evaluation algorithms</td>
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<td>IDEAL</td>
<td>Illinois Debris-Mitigation for EUV Applications Laboratory (U.S.)</td>
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<tr>
<td>IEA</td>
<td>ion energy analyzer</td>
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<tr>
<td>IEUVI</td>
<td>International EUV Initiative</td>
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<td>IF</td>
<td>intermediate focus</td>
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<tr>
<td>IGBT</td>
<td>insulated gate bipolar transistor</td>
</tr>
<tr>
<td>IMPACT</td>
<td>Interaction of Materials with charged Particles And Components Testing</td>
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<tr>
<td>IP</td>
<td>ion probe</td>
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<tr>
<td>IR</td>
<td>infrared</td>
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<tr>
<td>IRD</td>
<td>International Radiation Detectors</td>
</tr>
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<td>ISMT</td>
<td>International SEMATECH</td>
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<td>ITRS</td>
<td><em>International Technology Roadmap for Semiconductors</em></td>
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<td>KIAM</td>
<td>Keldysh Institute of Applied Mathematics (Russia)</td>
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<td>LBNL</td>
<td>Lawrence Berkeley National Laboratory (U.S.)</td>
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<td>LEISS</td>
<td>low-energy ion scattering spectroscopy</td>
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<td>LER</td>
<td>line edge roughness</td>
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<td>LLNL</td>
<td>Lawrence Livermore National Laboratory (U.S.)</td>
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<td>LPL</td>
<td>Laser Plasma Laboratory (U.S.)</td>
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<td>LPP</td>
<td>laser-produced plasma</td>
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<td>LTE</td>
<td>local thermodynamic equilibrium</td>
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<td>MCDF</td>
<td>multiconfiguration Dirac-Fock</td>
</tr>
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<td>MCHF</td>
<td>multiconfiguration Hartree-Fock</td>
</tr>
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<td>MCP</td>
<td>microchannel plate</td>
</tr>
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<td>MCRT</td>
<td>Monte Carlo radiation transport</td>
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<td>MCS</td>
<td>multicomponent system</td>
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<td>MET</td>
<td>microexposure tool</td>
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<td>METI</td>
<td>Ministry of Economy, Trade, and Industry (Japan)</td>
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<td>MHD</td>
<td>magnetohydrodynamics</td>
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<td>MHRDR</td>
<td>magnetohydronradiative-dynamic research</td>
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<td>ML</td>
<td>multilayer</td>
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<td>MLM</td>
<td>multilayer mirror</td>
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<td>MO</td>
<td>master oscillator</td>
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<tr>
<td>MOPA</td>
<td>master oscillator–power amplifier</td>
</tr>
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<td>MPC</td>
<td>magnetic pulse compression</td>
</tr>
<tr>
<td>MSEM</td>
<td>modified semiempirical method</td>
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<tr>
<td>Mo/Si</td>
<td>molybdenum on silicon</td>
</tr>
<tr>
<td>MTBF</td>
<td>mean time between failure</td>
</tr>
<tr>
<td>MTTR</td>
<td>mean time to repair</td>
</tr>
<tr>
<td>NA</td>
<td>numerical aperture</td>
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<td>NEDO</td>
<td>New Energy and Industrial Technology Development Organization (Japan)</td>
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<td>NGC</td>
<td>Northrop Grumman Corporation (U.S.)</td>
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<td>NGL</td>
<td>next-generation lithography</td>
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<tr>
<td>NIST</td>
<td>National Institute of Standards and Technology (U.S.)</td>
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<td>NLTE</td>
<td>non-local thermodynamic equilibrium</td>
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<td>NSLS</td>
<td>National Synchrotron Light Source (U.S.)</td>
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<tr>
<td>OOB</td>
<td>out-of-band</td>
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<td>ORNL</td>
<td>Oak Ridge National Laboratory (U.S.)</td>
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<td>PBN</td>
<td>pyrolytic boron nitride</td>
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<td>PE</td>
<td>potential energy</td>
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<tr>
<td>PMMA</td>
<td>poly(methyl methacrylate)</td>
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<td>PO</td>
<td>projection optics</td>
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<td>POM</td>
<td>polyacetal</td>
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<td>POPA</td>
<td>power-oscillator–power-amplifier</td>
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<td>PREUVE</td>
<td>PRoject Extreme Ultraviolet (France)</td>
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<td>PS</td>
<td>preferential sputtering</td>
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<td>PSPDI</td>
<td>phase-shifting point-diffraction interferometer</td>
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<td>PTB</td>
<td>Physikalisch-Technische Bundesanstalt (Germany)</td>
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<td>PV</td>
<td>peak to valley</td>
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<td>PVD</td>
<td>physical vapor deposition</td>
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<td>PZT</td>
<td>lead zirconium titanate</td>
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<td>QCM</td>
<td>quartz crystal microbalance</td>
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<td>QCM-DCU</td>
<td>quartz crystal microbalance–dual-crystal unit</td>
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<td>RAL</td>
<td>Rutherford Appleton Laboratory (U.K.)</td>
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<tr>
<td>RC</td>
<td>radiative collapse</td>
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<tr>
<td>RC</td>
<td>resistive capacitance (time constant)</td>
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<td>RDE</td>
<td>rotating-disk electrode</td>
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<tr>
<td>RED</td>
<td>radiation-enhanced diffusion</td>
</tr>
<tr>
<td>RES</td>
<td>radiation-enhanced sublimation</td>
</tr>
<tr>
<td>rf</td>
<td>radio frequency</td>
</tr>
<tr>
<td>RGA</td>
<td>residual gas analyzer</td>
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<td>RIS</td>
<td>radiation-induced segregation</td>
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<tr>
<td>RMDU</td>
<td>rotating multidischarge unit</td>
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<td>RMHD</td>
<td>radiative magnetohydrodynamics</td>
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<td>RTE</td>
<td>radiation transport equation</td>
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<td>SBS</td>
<td>stimulated Brillouin scattering</td>
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<tr>
<td>SCDF</td>
<td>single-configuration Dirac-Fock</td>
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<tr>
<td>SCO</td>
<td>superconfiguration code</td>
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<tr>
<td>SCOPE</td>
<td>Surface Cleaning of Optics by Plasma Exposure (U.S.)</td>
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<td>SEM</td>
<td>scanning electron microscopy</td>
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<td>SHG</td>
<td>second-harmonic generator</td>
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<td>SHM</td>
<td>screened hydrogenic model</td>
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<td>SIMS</td>
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<td>slm</td>
<td>standard liters per minute</td>
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<td>SOSA</td>
<td>spin-orbit split array</td>
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<td>SPF</td>
<td>spectral purity filter</td>
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<td>SRC</td>
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<tr>
<td>SRIM</td>
<td>Stopping and Range of Ions in Matter</td>
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<tr>
<td>STA</td>
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<tr>
<td>STM</td>
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<td>Synchrotron Ultraviolet Radiation Facility (at NIST)</td>
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<td>TBD</td>
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<td>TDLDA</td>
<td>time-dependent local density approximation</td>
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<td>TE</td>
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<td>Thomas-Fermi</td>
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<td>transmission grating spectrograph</td>
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<td>turbomolecular pump</td>
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