EUV Sources for Lithography
EUV Sources
for Lithography

Vivek Bakshi

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Bellingham, Washington USA
I dedicate this book to my parents,
wife, and daughter
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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 Krücklen, 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.

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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.

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<th>Institution</th>
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<tbody>
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<td>Ushio Inc., Japan</td>
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<tr>
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<td>EPPRA sas, France</td>
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<td>Northrop Grumman Corporation, USA</td>
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<td>Peter Zink</td>
<td>Philips Research Laboratories, Germany</td>
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# List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>AA</td>
<td>average atom</td>
</tr>
<tr>
<td>ACR</td>
<td>absolute cryogenic radiometer</td>
</tr>
<tr>
<td>ADM</td>
<td>angular distribution monitor</td>
</tr>
<tr>
<td>AEM</td>
<td>Auger electron microscopy</td>
</tr>
<tr>
<td>AES</td>
<td>Auger electron spectroscopy</td>
</tr>
<tr>
<td>AFM</td>
<td>atomic force microscopy</td>
</tr>
<tr>
<td>AIM</td>
<td>aerial-image microscope</td>
</tr>
<tr>
<td>ALS</td>
<td>Advanced Light Source (U.S.)</td>
</tr>
<tr>
<td>ANL</td>
<td>Argonne National Laboratory (U.S.)</td>
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<tr>
<td>AO</td>
<td>acousto-optical</td>
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<tr>
<td>arb.</td>
<td>arbitrary</td>
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<tr>
<td>ASD</td>
<td>axially symmetrical discharge</td>
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<tr>
<td>a.u.</td>
<td>arbitrary units</td>
</tr>
<tr>
<td>BCA</td>
<td>binary collision approximation</td>
</tr>
<tr>
<td>BW</td>
<td>bandwidth</td>
</tr>
<tr>
<td>CBM</td>
<td>carbon-based materials</td>
</tr>
<tr>
<td>CBS</td>
<td>collision-based spectroscopy</td>
</tr>
<tr>
<td>CCD</td>
<td>charge-coupled device</td>
</tr>
<tr>
<td>CE</td>
<td>conversion efficiency</td>
</tr>
<tr>
<td>CES</td>
<td>charged-exchange spectroscopy</td>
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<tr>
<td>CF</td>
<td>ConFlat</td>
</tr>
<tr>
<td>CFC</td>
<td>carbon-fiber composite</td>
</tr>
<tr>
<td>CI</td>
<td>configuration interaction</td>
</tr>
<tr>
<td>CM</td>
<td>collisional mixing</td>
</tr>
<tr>
<td>CO</td>
<td>condenser optic</td>
</tr>
<tr>
<td>CoO</td>
<td>cost of ownership</td>
</tr>
<tr>
<td>COR</td>
<td>condenser-optic region</td>
</tr>
<tr>
<td>CR</td>
<td>collisional radiative</td>
</tr>
<tr>
<td>CRE</td>
<td>collisional radiative equilibrium</td>
</tr>
<tr>
<td>CRM</td>
<td>collisional radiative mode</td>
</tr>
<tr>
<td>CTE</td>
<td>coefficient of thermal expansion</td>
</tr>
<tr>
<td>cw</td>
<td>continuous wave</td>
</tr>
<tr>
<td>CXRO</td>
<td>Center for X-ray Optics (at LBNL, U.S.)</td>
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<td>DCA</td>
<td>direct configuration accounting</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<td>--------------</td>
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<tr>
<td>DCU</td>
<td>dual-crystal unit</td>
</tr>
<tr>
<td>DF</td>
<td>Dirac-Fock</td>
</tr>
<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>
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<td>DPF</td>
<td>dense plasma focus</td>
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<tr>
<td>DPP</td>
<td>discharge-produced plasma</td>
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<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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<tr>
<td>DUV</td>
<td>deep ultraviolet</td>
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<tr>
<td>DWA</td>
<td>distorted-wave approximation</td>
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<tr>
<td>EBIT</td>
<td>electron-beam ion trap</td>
</tr>
<tr>
<td>EDX</td>
<td>energy dispersive x-ray spectroscopy</td>
</tr>
<tr>
<td>EM</td>
<td>electromagnetic</td>
</tr>
<tr>
<td>EO</td>
<td>electro optical</td>
</tr>
<tr>
<td>EOS</td>
<td>equation of state</td>
</tr>
<tr>
<td>ES</td>
<td>electrostatic analyzer</td>
</tr>
<tr>
<td>ESA</td>
<td>spherical-sector electrostatic energy analyzer</td>
</tr>
<tr>
<td>ESIEA</td>
<td>electrostatic ion energy analyzer</td>
</tr>
<tr>
<td>ESR</td>
<td>electrical substitution radiometer</td>
</tr>
<tr>
<td>ETS</td>
<td>Engineering Test Stand</td>
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<tr>
<td>EUV</td>
<td>extreme ultraviolet</td>
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<td>EUVA</td>
<td>Extreme Ultraviolet Lithography System Development Association (Japan)</td>
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<td>EUVL</td>
<td>extreme ultraviolet lithography</td>
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<tr>
<td>EUV LLC</td>
<td>EUV Limited Liability Corporation</td>
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<tr>
<td>FAC</td>
<td>Flexible Atomic Code</td>
</tr>
<tr>
<td>FC</td>
<td>Flying Circus</td>
</tr>
<tr>
<td>FDWG</td>
<td>Fundamental Data Working Group (of SEMATECH)</td>
</tr>
<tr>
<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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<tr>
<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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<tr>
<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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<tr>
<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>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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<tr>
<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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<tr>
<td>IBA</td>
<td>inverse bremsstrahlung absorption</td>
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<td>IC</td>
<td>integrated circuit</td>
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<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>
</tr>
<tr>
<td>IEUVI</td>
<td>International EUV Initiative</td>
</tr>
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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>
</tr>
<tr>
<td>IP</td>
<td>ion probe</td>
</tr>
<tr>
<td>IR</td>
<td>infrared</td>
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<tr>
<td>IRD</td>
<td>International Radiation Detectors</td>
</tr>
<tr>
<td>ISMT</td>
<td>International SEMATECH</td>
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<td>ITRS</td>
<td>International Technology Roadmap for Semiconductors</td>
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<td>KIAM</td>
<td>Keldysh Institute of Applied Mathematics (Russia)</td>
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<td>LBNL</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>
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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>
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<td>MCHF</td>
<td>multiconfiguration Hartree-Fock</td>
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<tr>
<td>MCP</td>
<td>microchannel plate</td>
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<tr>
<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>magnetohydrodynamic-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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<tr>
<td>MO</td>
<td>master oscillator</td>
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<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>MOPA</td>
<td>master oscillator–power amplifier</td>
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<td>MPC</td>
<td>magnetic pulse compression</td>
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<td>MSEM</td>
<td>modified semiempirical method</td>
</tr>
<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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<tr>
<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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<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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<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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<tr>
<td>PE</td>
<td>potential energy</td>
</tr>
<tr>
<td>PMMA</td>
<td>poly(methyl methacrylate)</td>
</tr>
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<td>PO</td>
<td>projection optics</td>
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<tr>
<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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<tr>
<td>PS</td>
<td>preferential sputtering</td>
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<tr>
<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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<tr>
<td>PV</td>
<td>peak to valley</td>
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<tr>
<td>PVD</td>
<td>physical vapor deposition</td>
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<tr>
<td>PZT</td>
<td>lead zirconium titanate</td>
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<tr>
<td>QCM</td>
<td>quartz crystal microbalance</td>
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<tr>
<td>QCM-DCU</td>
<td>quartz crystal microbalance–dual-crystal unit</td>
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<tr>
<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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<td>RED</td>
<td>radiation-enhanced diffusion</td>
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<td>RES</td>
<td>radiation-enhanced sublimation</td>
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<tr>
<td>rf</td>
<td>radio frequency</td>
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<td>RGA</td>
<td>residual gas analyzer</td>
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<td>RIS</td>
<td>radiation-induced segregation</td>
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<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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<tr>
<td>SBS</td>
<td>stimulated Brillouin scattering</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>SCDF</td>
<td>single-configuration Dirac-Fock</td>
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<td>SCO</td>
<td>superconfiguration code</td>
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<td>SCOPE</td>
<td>Surface Cleaning of Optics by Plasma Exposure (U.S.)</td>
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<td>SEM</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>secondary-ion mass spectroscopy</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>
<td>Semiconductor Research Corporation (U.S.)</td>
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<td>SRIM</td>
<td>Stopping and Range of Ions in Matter</td>
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<td>STA</td>
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<td>STE</td>
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<td>STM</td>
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<td>SURF II</td>
<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>TGS</td>
<td>transmission grating spectrograph</td>
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<td>turbomolecular pump</td>
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<td>TOF</td>
<td>time-of-flight</td>
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<td>TPS</td>
<td>Thomson parabola spectrometer</td>
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<td>TRINITI</td>
<td>Troitsk Institute of Innovation and Fusion Research (Russia)</td>
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<td>TVD</td>
<td>total variation diminishing</td>
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<td>TWG</td>
<td>Technical Working Group</td>
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<td>UHV</td>
<td>ultrahigh vacuum</td>
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<td>VUV</td>
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<td>WDS</td>
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<td>WS</td>
<td>working standard</td>
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<td>XPS</td>
<td>x-ray photoelectron spectroscopy</td>
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