EUV Sources
for Lithography
EUV Sources for Lithography

Vivek Bakshi
I dedicate this book to my parents, wife, and daughter
# Contents

**Preface**  
*Vivek Bakshi*  
xxix

**Introduction**  
*Kevin Kemp*  
xxi

**List of Contributors**  
xxiii

**List of Abbreviations**  
xxxiii

## Section I: Introduction and Technology Review  
1

### Chapter 1 EUV Source Technology: Challenges and Status  
*Vivek Bakshi*  
3

1.1 Introduction  
4
1.2 Conversion Efficiency of EUV Sources  
4
1.3 EUV Source Power  
9
1.4 Source Components and Their Lifetimes  
19
1.5 Summary and Future Outlook  
20

**References**  
21

### Chapter 2 EUV Source Requirements for EUV Lithography  
*Kazuya Ota, Yutaka Watanabe, Vadim Banine, and Hans Franken*  
27

2.1 Introduction and Background  
27
2.2 Source Requirements  
29
2.3 Component Degradation  
38
2.4 Cost of Ownership  
39
2.5 Conclusions  
41

**Acknowledgments**  
41

**References**  
41

## Section II: Fundamentals and Modeling  
45

### Chapter 3 Atomic Xenon Data  
*John D. Gillaspy*  
47

3.1 Introduction  
47
3.2 Specification of the Subtypes of Fundamental Atomic Data Needed 49
3.3 Overview and Current Status of Available Data for Xenon \( q = 7 \) to \( q = 18 \) 53
3.4 References to Data for the Less-Critical Charge States \( q < 7 \) or \( q > 18 \) of Xenon 54
3.5 Benchmarking Input Data 54
3.6 Benchmarking Output Data 55
3.7 Outlook and Future Data Needs 56
Acknowledgments 57
References (for main text) 57
Appendix A: International SEMATECH’s Fundamental Data Working Group 59
Appendix B: Xenon Atomic Data 59

Chapter 4 Atomic Tin Data 113

4.1 Introduction 113
4.2 Theoretical Approach 114
4.3 Results of the Calculations 115
4.4 Registration of Sn Plasma Spectra 115
4.5 Primary Classification on Charge States 117
4.6 Conclusion 120
Acknowledgments 120
Appendix: Results of Theoretical Calculations of Sn Ion Spectra 121
References 147

Chapter 5 Atomic Physics of Highly Charged Ions and the Case for Sn as a Source Material 149
Gerry O’Sullivan, Anthony Cummings, Padraig Dunne, Patrick Hayden, Luke McKinney, Nicola Murphy, and John White

5.1 Introduction and Background 149
5.2 The Case for Xenon 151
5.3 Alternatives to Xenon; the Case for Tin 156
5.4 Conclusions 167
Acknowledgments 167
References 168

Chapter 6 Radiative Collapse in \( Z \) Pinches 175

6.1 Introduction 175
6.2 Formation of Pinch Columns 176
6.3 Discharge Source for EUVL: High-Power, High-CE Alternative Concept Source 178
6.4 Neck Instabilities in Pinch Plasmas: Radiative Collapse 179
6.5 Plasma-Column Energy Balance; Pease-Braginskii Current; Critical Current for Heavy-Ion Plasmas 180
6.6 Neck Development Scenario 183
6.7 Experimental Observation of Neck Instabilities; Plasma Outflow 185
6.8 Dissipation of Electrical Energy in the Discharge 186
6.9 Equilibrium Radius; EUV Source Size 187
6.10 Equilibrium Radius versus Linear Density Trajectory 189
6.11 Stability of Radiative-Collapse Trajectory, EUV Yield, and Shot-to-Shot Reproducibility 190
6.12 Axial Size of the EUV Source; Zippering Effect 191
6.13 Conclusions 193
Acknowledgments 193
References 193

Chapter 7  **Fundamentals and Limits of Plasma-based EUV Sources**  197

*Rainer Lebert, Thomas Krücken, and H.-J. Kunze*

7.1 Introduction 197
7.2 Required Parameters of EUV Sources 199
7.3 Fundamental Limits 201
7.4 Fundamental Processes 205
7.5 Factors Influencing the Radiative Yield 208
7.6 Plasma Simulation: Tool for Source Optimization 215
7.7 Atomic Physics, Radiation, and Ionization Modeling 216
7.8 MHD Description of the Pinch Phase of the Discharge 218
7.9 Other Important Issues 219
Acknowledgments 219
References 219

Chapter 8  **Z\(^\ast\)** Code for DPP and LPP Source Modeling 223

*Sergey V. Zakharov, Vladimir G. Novikov, and Peter Choi*

8.1 Introduction 224
8.2 Fundamentals of the Physics of EUV-Emitting Plasmas 225
8.3 Computational RMHD Code Z\(^\ast\) 236
8.4 EUV Radiation Source Simulations 246
8.5 Summary 264
Acknowledgments 267
Appendix A: Analytical Solution for the Axially Inhomogenous Capillary Discharge 267
Appendix B: Estimations for the Motion Dynamics of a Sheath in the Ionized Gas via the Snowplow Model 269
Appendix C: Calculation of the Laser Energy Transport Process 271
References 271

Chapter 9  HEIGHTS-EUV Package for DPP Source Modeling 277
A. Hassanein, V. Morozov, V. Sizyuk, V. Tolkach, and B. Rice

9.1 Introduction 277
9.2 Magnetohydrodynamics 279
9.3 External Electric Circuit 281
9.4 Detailed Radiation Transport 282
9.5 Atomic Physics and Opacities 286
9.6 Results and Discussion 294
9.7 Conclusion 296
Acknowledgments 296
References 296

Chapter 10  Modeling LPP Sources 299
Moza Al-Rabban, Martin Richardson, Howard Scott, Franck Gilleron, Michel Poirier, and Thomas Blenski

10.1 Introduction 300
10.2 EUVL Source Requirements 301
10.3 Physical Processes in Laser Plasmas 303
10.4 Modeling Laser-Target Interactions and Plasma Expansion 306
10.5 Atomic Physics Modeling of Laser Plasmas 312
10.6 Future Trends 329
Acknowledgments 330
References 330

Chapter 11  Conversion Efficiency of LPP Sources 339
Katsunobu Nishihara, Akira Sasaki, Atsushi Sunahara, and Takeshi Nishikawa

11.1 Introduction 339
11.2 Design Window for Practical Use 341
11.3 Power Balance Model 343
11.4 Atomic Models and Radiation Hydrodynamic Code 348
11.5 Conversion Efficiency for Tin and Xenon 353
11.6 Discussion and Summary 364
Acknowledgments 365
References 365

Section III: Plasma Pinch Sources 371

Chapter 12  Dense Plasma Focus Source 373
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.1 Introduction</td>
<td>373</td>
</tr>
<tr>
<td>12.2 Overview of the Source</td>
<td>374</td>
</tr>
<tr>
<td>12.3 Pulsed-Power Development</td>
<td>375</td>
</tr>
<tr>
<td>12.4 EUV Output Energy and Conversion Efficiency</td>
<td>376</td>
</tr>
<tr>
<td>12.5 Operation at High Repetition Rates</td>
<td>376</td>
</tr>
<tr>
<td>12.6 Thermal Management</td>
<td>378</td>
</tr>
<tr>
<td>12.7 EUV Source Size and Spatial and Angular Distribution</td>
<td>380</td>
</tr>
<tr>
<td>12.8 EUV Spectra</td>
<td>380</td>
</tr>
<tr>
<td>12.9 Spectral and Plasma Modeling</td>
<td>382</td>
</tr>
<tr>
<td>12.10 Metal Target Elements</td>
<td>383</td>
</tr>
<tr>
<td>12.11 Debris Mitigation and Contamination Studies</td>
<td>385</td>
</tr>
<tr>
<td>12.12 EUV Collector</td>
<td>386</td>
</tr>
<tr>
<td>12.13 Lifetime Limitations and Power Scaling</td>
<td>387</td>
</tr>
<tr>
<td>12.14 Summary and Conclusion</td>
<td>388</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>389</td>
</tr>
<tr>
<td>References</td>
<td>389</td>
</tr>
</tbody>
</table>

**Chapter 13 Hollow-Cathode-Triggered Plasma Pinch Discharge**

Joseph Pankert, Klaus Bergmann, Rolf Wester, Jürgen Klein, Willi Neff, Oliver Rosier, Stefan Seiwert, Christopher Smith, Sven Probst, Dominik Vaudrevange, Guido Siemons, Rolf Apetz, Jeroen Jonkers, Michael Loeken, Günther Derra, Thomas Krücken, and Peter Zink

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.1 Introduction</td>
<td>395</td>
</tr>
<tr>
<td>13.2 Physics of EUV Sources based on Hollow-Cathode-Triggered Gas Discharges</td>
<td>396</td>
</tr>
<tr>
<td>13.3 The Philips HCT Source: Design and Results</td>
<td>401</td>
</tr>
<tr>
<td>13.4 Summary and Outlook</td>
<td>410</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>410</td>
</tr>
<tr>
<td>References</td>
<td>410</td>
</tr>
</tbody>
</table>

**Chapter 14 High-Power GDPP Z-Pinch EUV Source Technology**

Uwe Stamm, Guido Schriever, and Jürgen Kleinschmidt

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.1 Introduction</td>
<td>413</td>
</tr>
<tr>
<td>14.2 Physics of the Z-Pinch Discharge and EUV Generation</td>
<td>418</td>
</tr>
<tr>
<td>14.3 Emitter Materials for 13.5-nm Z-Pinch Sources</td>
<td>421</td>
</tr>
<tr>
<td>14.4 Discharge Electrode System, Source Collector, and Electrode Lifetime</td>
<td>423</td>
</tr>
<tr>
<td>14.5 Pulsed Power Excitation of Z Pinches</td>
<td>427</td>
</tr>
<tr>
<td>14.6 Discharge-Electrode Thermal Management Technology</td>
<td>431</td>
</tr>
<tr>
<td>14.7 Debris Mitigation and Collector-Optics Protection</td>
<td>433</td>
</tr>
<tr>
<td>14.8 First Commercial Sources for Exposure Tools—EUV Source XTS 13-35</td>
<td>435</td>
</tr>
<tr>
<td>14.9 Scaling of Z-Pinch Power and Lifetime Performance to β-Tool and HVM Requirements</td>
<td>439</td>
</tr>
</tbody>
</table>
14.10 Path to Meet Remaining Challenges for HVM GDPP Sources—Lifetime Improvement of Discharge Electrode System and Source Collector Optics for Tin Fuel 445
14.11 Summary and Conclusion 448
Acknowledgments 448
References 449

Chapter 15  Star Pinch EUV Source 453
Malcolm W. McGeoch
15.1 Generic EUV Source Factors 453
15.2 Directed Discharges 459
15.3 Current Star Pinch Performance 465
15.4 Scaling to High-Volume Manufacturing 471
References 473

Chapter 16  Xenon and Tin Pinch Discharge Sources 477
16.1 Introduction 477
16.2 Pinch Effect 478
16.3 EUV Source Using Xe 481
16.4 Some Approaches to Meet HVM Requirements 488
16.5 Pinch Discharges Based on Sn Vapor and Gas Mixtures 491
16.6 Excimer-Laser-Initiated Pinch Discharge in Sn 495
16.7 Conclusions 500
Acknowledgments 501
References 501

Chapter 17  Capillary Z-Pinch Source 505
Yusuke Teramoto, Hiroto Sato, and Masaki Yoshioka
17.1 Introduction 505
17.2 Discharge Head and Magnetic Pulse Compression Generator 506
17.3 Diagnostics 507
17.4 Experimental Results 509
17.5 Conclusions 520
Acknowledgments 521
References 521

Chapter 18  Plasma Capillary Source 523
Željko Andreić, Samir Ellwi, and H.-J. Kunze
18.1 Introduction 523
18.2 Theoretical Modeling 524
18.3 Gas-Filled Capillaries 524
Chapter 22  Driver Laser, Xenon Target, and System Development for LPP Sources 607
Akira Endo

22.1 Introduction 607
22.2 High-Power Driver Laser 608
22.3 Xenon Targets 610
22.4 Light-Source EUV Characteristics 611
22.5 Summary 615
Acknowledgment 615
References 616

Chapter 23  Liquid-Xenon-Jet LPP Source 619
Björn A. M. Hansson and Hans M. Hertz

23.1 Introduction 620
23.2 Liquid-Xenon-Jet Laser Plasma Generation 624
23.3 Source Requirements and Design Example 629
23.4 Source Characterization 630
23.5 Lifetime 636
23.6 Summary 640
Acknowledgments 641
References 641

Chapter 24  LPP Source Development and Operation in the Engineering Test Stand 649
John E. M. Goldsmith, Glenn D. Kubiak, and William P. Ballard

24.1 Introduction 649
24.2 Early Source Development at Sandia 651
24.3 ETS Source Development 653
24.4 Integration of the High-Power Source into the ETS 657
24.5 ETS Operation with the High-Power Source 661
24.6 Conclusion 663
Acknowledgments 665
References 665

Chapter 25  Xenon Target and High-Power Laser Module Development for LPP Sources 669

25.1 Introduction 669
25.2 Laser Module 669
25.3 Xenon Target Development 674
Chapter 26  Laser Plasma EUV Sources based on Droplet Target Technology

Martin Richardson, Chiew-Seng Koay, Kazutoshi Takenoshita, Christian Keyser, Simi George, Moza Al-Rabban, and Vivek Bakshi

26.1 Introduction 687
26.2 Laser Interaction with Mass-Limited Spherical Targets 691
26.3 Plasma Dynamics of Droplet Laser Plasmas 695
26.4 EUV Emission from Laser Plasma Droplet Sources 701
26.5 Ion Emission from Droplet Laser Plasmas 704
26.6 Particle Emission from Laser Plasmas 707
26.7 Inhibition of Ion and Particle Emission 710
26.8 High-Power and Long-Life Target Scenarios 713
26.9 Summary 714
Acknowledgments 714
References 715

Section V: EUV Source Metrology

Chapter 27  Flying Circus EUV Source Metrology and Source Development Assessment

Fred Bijkerk, Santi Alonso van der Westen, Caspar Bruineman, Robert Huiting, René de Bruijn, and Remko Stuik

27.1 Historical Overview of Metrology Development and Standardization 721
27.2 Metrology Concept 722
27.3 EUV Source Metrology Calibration Procedures 723
27.4 FC Source Progress Assessment 725
27.5 Diagnostic Extensions and New Developments 727
27.6 Summary and Future Directions 729
Acknowledgments 730
References 731

Chapter 28  Plasma Diagnostic Techniques

Eric C. Benck

28.1 Introduction 735
28.2 Surface Accumulators 736
28.3 Plasma Imaging 738
28.4 Electron Diagnostics 742
28.5 Ion Diagnostics 745
28.6 Neutral-Atom Detectors 752
Chapter 29 Metrology for EUVL Sources and Tools
Steve Grantham, Charles Tarrio, Robert Vest, and Thomas Lucatorto

29.1 Introduction 760
29.2 NIST EUV Sources for Metrology 760
29.3 Inband EUV Power Instrumentation 764
29.4 Reflectometry 765
29.5 Detector Characterization 769
29.6 Calibration of EUV Radiometry Tools 777
29.7 Conclusion 780
References 780

Chapter 30 Calibration of Detectors and Tools for EUV-Source Metrology
Frank Scholze and Gerhard Ulm

30.1 Introduction 785
30.2 Synchrotron Radiation Beamlines for EUV Metrology 786
30.3 Instrumentation for Detector Calibration and Optics Characterization 792
30.4 Semiconductor Photodiodes as Reference Detector Standards 797
30.5 Spectrally Filtered Tools and Spectrographs 807
30.6 Conclusions and Future Needs 813
Acknowledgments 815
References 815

Section VI: Other Types of EUV Sources

Chapter 31 Electron-based EUV Sources for At-Wavelength Metrology
André Egbert and Boris N. Chichkov

31.1 The EUV Tube—an Old Solution for New Applications 823
31.2 Characteristics of the EUV Tube 825
31.3 Applications of the EUV Tube 833
31.4 Summary and Outlook 839
Acknowledgments 839
References 839

Chapter 32 Synchrotron Radiation Sources for EUVL Applications
Obert R. Wood, II and Alastair A. MacDowell

32.1 Electron Storage Rings and Synchrotron Radiation 841
32.2 Characteristics of Synchrotron Radiation 845
# Contents

32.3 Survey of Current Synchrotron Radiation Facilities 848  
32.4 Selected Applications of Synchrotron Radiation in EUVL 849  
32.5 Conclusions and Suggestions for Future Work 864  
References 865  

Section VII: EUV Source Components 871  

Chapter 33 Grazing-Incidence EUV Collectors 873  
*Piotr Marczuk and Wilhelm Egle*  
33.1 Introduction 873  
33.2 EUV Collectors: General Considerations 875  
33.3 Grazing-Incidence EUV Collectors 876  
33.4 Summary, Trends, and Challenges 890  
Acknowledgments 890  
References 891  

Chapter 34 Collection Efficiency of EUV Sources 893  
*Günther Derra and Wolfgang Singer*  
34.1 Introduction 893  
34.2 Etendue of Illumination Systems 894  
34.3 Determination of EUV Source Power 898  
34.4 Example Measurements at the HCT Pinch 904  
34.5 Conclusions 910  
Acknowledgments 912  
References 912  

Chapter 35 Electrode and Condenser Materials for Plasma Pinch Sources 915  
35.1 Introduction 916  
35.2 Electrode Thermal Response 917  
35.3 Materials Selection for Plasma Pinch Sources 925  
35.4 Testing of Materials in Plasma-Gun Facilities 932  
35.5 Modeling and Testing Condenser-Optic Response 946  
35.6 Conclusions 953  
References 953  

Chapter 36 Origin of Debris in EUV Sources and Its Mitigation 957  
*David N. Ruzic*  
36.1 Introduction 958  
36.2 Source Terms 958  
36.3 Standard Mitigation Techniques 969  
36.4 Mitigation through Plasma-based Secondary Ionization 976
Chapter 37  Erosion of Condenser Optics Exposed to EUV Sources 995
Leonard E. Klebanoff, Richard J. Anderson, Dean A. Buchenauer, Neal R. Fornaciari, and Hiroshi Komori

37.1 Introduction 995
37.2 Early Work on Condenser Erosion 998
37.3 Condenser Erosion Observations in the ETS 1003
37.4 Condenser Erosion Study Systems After the ETS 1007
37.5 Erosion Studies of EUVA 1016
37.6 Work in Other Laboratories 1028
Acknowledgments 1028
References 1029

Chapter 38  Potential Energy Sputtering of EUVL Materials 1033
Joshua M. Pomeroy, Laura P. Ratliff, John D. Gillaspy, and Saša Bajić

38.1 Introduction 1033
38.2 Interactions of HCIs with Solids 1034
38.3 Experimental Studies of PE Damage to EUVL Devices 1037
38.4 Implications and Outlook 1041
38.5 Summary 1041
Acknowledgments 1041
References 1042

Index 1045
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

Richard J. Anderson
Sandia National Laboratories, USA

Željko Andreić
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

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

Benoit Barthod
EXULITE Project
DSM/DRECAM/SPAM, CEA, France

T. Burtseva
Argonne National Laboratory, USA
List of Contributors

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
List of Contributors

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. Khristoforov
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
V. Krivtsun  
Institute for Spectroscopy Russian Academy of Sciences, Russia

Thomas Krücken  
Philips Research Laboratories, Germany

Glenn D. Kubiak  
Sandia National Laboratories, USA

H.-J. Kunze  
Ruhr University, Germany

Rainer Lebert  
AIXUV GmbH, Germany

Michael Loeken  
Philips Extreme UV GmbH, Germany

Thomas Lucatorto  
National Institute of Standards and Technology (NIST), USA

Alastair A. MacDowell  
Lawrence Berkeley National Laboratory (LBNL), USA

Piotr Marczuk  
Carl Zeiss Laser Optics GmbH, Germany

Armando Martos  
Northrop Grumman Corporation, USA

Fernando Martos  
Northrop Grumman Corporation, USA

Malcolm W. McGeoch  
PLEX LLC, USA

R. D. McGregor  
Northrop Grumman Corporation, USA

Luke McKinney  
University College Dublin, Ireland

Stuart McNaught  
Northrop Grumman Corporation, USA

Stephan T. Melnychuk  
Cymer, Inc., USA

Valentin A. Mishchenko  
Troitsk Institute of Innovation and Fusion Research (TRINITI), Russia

Mark Michaelian  
Northrop Grumman Corporation, USA

V. Morozov  
Argonne National Laboratory, USA

Richard Moyer  
Northrop Grumman Corporation, USA

Nicola Murphy  
University College Dublin, Ireland

Katsunobu Nishihara  
Osaka University, Japan

Takeshi Nishikawa  
Okayama University, Japan

Willi Neff  
Fraunhofer Institut für Lasertechnik, Germany

Richard M. Ness  
Cymer, Inc., USA

Vladimir G. Novikov  
Keldysh Institute of Applied Mathematics Russian Academy of Sciences, Russia

Ian R. Oliver  
Cymer, Inc., USA

Rocco Orsini  
Northrop Grumman Corporation, USA

Gerry O’Sullivan  
University College Dublin, Ireland
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/DRECAMS/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/DRECAMS/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 Seiwerk
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
<table>
<thead>
<tr>
<th>Contributor</th>
<th>Institution/Company</th>
</tr>
</thead>
<tbody>
<tr>
<td>O. Yakushev</td>
<td>Institute for Spectroscopy Russian Academy of Sciences, Russia</td>
</tr>
<tr>
<td>Masaki Yoshioka</td>
<td>Ushio Inc., Japan</td>
</tr>
<tr>
<td>Sergey V. Zakharov</td>
<td>EPPRA sas, France</td>
</tr>
<tr>
<td>G. G. Zukakishvili</td>
<td>Institute for Spectroscopy Russian Academy of Sciences, Russia</td>
</tr>
<tr>
<td>James Zamel</td>
<td>Northrop Grumman Corporation, USA</td>
</tr>
<tr>
<td>Peter Zink</td>
<td>Philips Research Laboratories, Germany</td>
</tr>
<tr>
<td>Peter Zink</td>
<td>Philips Research Laboratories, Germany</td>
</tr>
</tbody>
</table>
## List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<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>
</tr>
<tr>
<td>AO</td>
<td>acousto-optical</td>
</tr>
<tr>
<td>arb.</td>
<td>arbitrary</td>
</tr>
<tr>
<td>ASD</td>
<td>axially symmetrical discharge</td>
</tr>
<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>
</tr>
<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>
</tr>
<tr>
<td>DCA</td>
<td>direct configuration accounting</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>------------------------------</td>
</tr>
<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>
<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>
</tr>
<tr>
<td>DTA</td>
<td>detailed term accounting</td>
</tr>
<tr>
<td>DUV</td>
<td>deep ultraviolet</td>
</tr>
<tr>
<td>DWA</td>
<td>distorted-wave approximation</td>
</tr>
<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>
</tr>
<tr>
<td>EUV</td>
<td>extreme ultraviolet</td>
</tr>
<tr>
<td>EUVA</td>
<td>Extreme Ultraviolet Lithography System Development Association (Japan)</td>
</tr>
<tr>
<td>EUVL</td>
<td>extreme ultraviolet lithography</td>
</tr>
<tr>
<td>EUV LLC</td>
<td>EUV Limited Liability Corporation</td>
</tr>
<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>
</tr>
<tr>
<td>FMEA</td>
<td>failure-mode and effect analysis</td>
</tr>
<tr>
<td>FOM</td>
<td>Fundamenteel Onderzoek der Materie (The Netherlands)</td>
</tr>
<tr>
<td>FT</td>
<td>foil trap</td>
</tr>
<tr>
<td>FWHM</td>
<td>full width at half maximum</td>
</tr>
<tr>
<td>GA</td>
<td>Gibbsian adsorption</td>
</tr>
<tr>
<td>GDPP</td>
<td>gas-discharge produced plasma</td>
</tr>
<tr>
<td>GEA</td>
<td>gridded energy analyzer</td>
</tr>
<tr>
<td>GIM</td>
<td>grazing-incidence mirror</td>
</tr>
<tr>
<td>HCI</td>
<td>highly charged ions</td>
</tr>
<tr>
<td>HCT</td>
<td>hollow-cathode triggered</td>
</tr>
<tr>
<td>HEDP</td>
<td>high-energy-density physics</td>
</tr>
<tr>
<td>HEW</td>
<td>half energy width</td>
</tr>
<tr>
<td>HF</td>
<td>Hartree-Fock</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>HFR</td>
<td>Hartree-Fock approximation with relativistic extensions</td>
</tr>
<tr>
<td>HFS</td>
<td>Hartree-Fock-Slater</td>
</tr>
<tr>
<td>HLI</td>
<td>Helmholtz-Lagrange invariant</td>
</tr>
<tr>
<td>HULLAC</td>
<td>Hebrew University Lawrence Livermore Atomic Code</td>
</tr>
<tr>
<td>HV</td>
<td>high voltage</td>
</tr>
<tr>
<td>HVE</td>
<td>high-voltage electrode</td>
</tr>
<tr>
<td>HVM</td>
<td>high-volume manufacturing</td>
</tr>
<tr>
<td>IBA</td>
<td>inverse bremsstrahlung absorption</td>
</tr>
<tr>
<td>IC</td>
<td>integrated circuit</td>
</tr>
<tr>
<td>ICE</td>
<td>intrinsic conversion efficiency</td>
</tr>
<tr>
<td>IDEA</td>
<td>interferometric data evaluation algorithms</td>
</tr>
<tr>
<td>IDEAL</td>
<td>Illinois Debris-Mitigation for EUV Applications Laboratory (U.S.)</td>
</tr>
<tr>
<td>IEA</td>
<td>ion energy analyzer</td>
</tr>
<tr>
<td>IEUVI</td>
<td>International EUV Initiative</td>
</tr>
<tr>
<td>IF</td>
<td>intermediate focus</td>
</tr>
<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>
</tr>
<tr>
<td>IRD</td>
<td>International Radiation Detectors</td>
</tr>
<tr>
<td>ISMT</td>
<td>International SEMATECH</td>
</tr>
<tr>
<td>ITRS</td>
<td><em>International Technology Roadmap for Semiconductors</em></td>
</tr>
<tr>
<td>KIAM</td>
<td>Keldysh Institute of Applied Mathematics (Russia)</td>
</tr>
<tr>
<td>LBNL</td>
<td>Lawrence Berkeley National Laboratory (U.S.)</td>
</tr>
<tr>
<td>LEISS</td>
<td>low-energy ion scattering spectroscopy</td>
</tr>
<tr>
<td>LER</td>
<td>line edge roughness</td>
</tr>
<tr>
<td>LLNL</td>
<td>Lawrence Livermore National Laboratory (U.S.)</td>
</tr>
<tr>
<td>LPL</td>
<td>Laser Plasma Laboratory (U.S.)</td>
</tr>
<tr>
<td>LPP</td>
<td>laser-produced plasma</td>
</tr>
<tr>
<td>LTE</td>
<td>local thermodynamic equilibrium</td>
</tr>
<tr>
<td>MCDF</td>
<td>multiconfiguration Dirac-Fock</td>
</tr>
<tr>
<td>MCHF</td>
<td>multiconfiguration Hartree-Fock</td>
</tr>
<tr>
<td>MCP</td>
<td>microchannel plate</td>
</tr>
<tr>
<td>MCRT</td>
<td>Monte Carlo radiation transport</td>
</tr>
<tr>
<td>MCS</td>
<td>multicomponent system</td>
</tr>
<tr>
<td>MET</td>
<td>microexposure tool</td>
</tr>
<tr>
<td>METI</td>
<td>Ministry of Economy, Trade, and Industry (Japan)</td>
</tr>
<tr>
<td>MHD</td>
<td>magnetohydrodynamics</td>
</tr>
<tr>
<td>MHRDR</td>
<td>magnetohydrodynamic-radiative-dynamic research</td>
</tr>
<tr>
<td>ML</td>
<td>multilayer</td>
</tr>
<tr>
<td>MLM</td>
<td>multilayer mirror</td>
</tr>
<tr>
<td>MO</td>
<td>master oscillator</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>MOPA</td>
<td>master oscillator–power amplifier</td>
</tr>
<tr>
<td>MPC</td>
<td>magnetic pulse compression</td>
</tr>
<tr>
<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>
</tr>
<tr>
<td>NEDO</td>
<td>New Energy and Industrial Technology Development Organization (Japan)</td>
</tr>
<tr>
<td>NGC</td>
<td>Northrop Grumman Corporation (U.S.)</td>
</tr>
<tr>
<td>NGL</td>
<td>next-generation lithography</td>
</tr>
<tr>
<td>NIST</td>
<td>National Institute of Standards and Technology (U.S.)</td>
</tr>
<tr>
<td>NLTE</td>
<td>non-local thermodynamic equilibrium</td>
</tr>
<tr>
<td>NSLS</td>
<td>National Synchrotron Light Source (U.S.)</td>
</tr>
<tr>
<td>OOB</td>
<td>out-of-band</td>
</tr>
<tr>
<td>ORNL</td>
<td>Oak Ridge National Laboratory (U.S.)</td>
</tr>
<tr>
<td>PBN</td>
<td>pyrolytic boron nitride</td>
</tr>
<tr>
<td>PE</td>
<td>potential energy</td>
</tr>
<tr>
<td>PMMA</td>
<td>poly(methyl methacrylate)</td>
</tr>
<tr>
<td>PO</td>
<td>projection optics</td>
</tr>
<tr>
<td>POM</td>
<td>polyacetal</td>
</tr>
<tr>
<td>POPA</td>
<td>power-oscillator–power-amplifier</td>
</tr>
<tr>
<td>PREUVE</td>
<td>PRoject Extreme Ultraviolet (France)</td>
</tr>
<tr>
<td>PS</td>
<td>preferential sputtering</td>
</tr>
<tr>
<td>PSPDI</td>
<td>phase-shifting point-diffraction interferometer</td>
</tr>
<tr>
<td>PTB</td>
<td>Physikalisch-Technische Bundesanstalt (Germany)</td>
</tr>
<tr>
<td>PV</td>
<td>peak to valley</td>
</tr>
<tr>
<td>PVD</td>
<td>physical vapor deposition</td>
</tr>
<tr>
<td>PZT</td>
<td>lead zirconium titanate</td>
</tr>
<tr>
<td>QCM</td>
<td>quartz crystal microbalance</td>
</tr>
<tr>
<td>QCM-DCU</td>
<td>quartz crystal microbalance–dual-crystal unit</td>
</tr>
<tr>
<td>RAL</td>
<td>Rutherford Appleton Laboratory (U.K.)</td>
</tr>
<tr>
<td>RC</td>
<td>radiative collapse</td>
</tr>
<tr>
<td>RC</td>
<td>resistive capacitance (time constant)</td>
</tr>
<tr>
<td>RDE</td>
<td>rotating-disk electrode</td>
</tr>
<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>
</tr>
<tr>
<td>RIS</td>
<td>radiation-induced segregation</td>
</tr>
<tr>
<td>RMDU</td>
<td>rotating multidischarge unit</td>
</tr>
<tr>
<td>RMHD</td>
<td>radiative magnetohydrodynamics</td>
</tr>
<tr>
<td>RTE</td>
<td>radiation transport equation</td>
</tr>
<tr>
<td>SBS</td>
<td>stimulated Brillouin scattering</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>SCDF</td>
<td>single-configuration Dirac-Fock</td>
</tr>
<tr>
<td>SCO</td>
<td>superconfiguration code</td>
</tr>
<tr>
<td>SCOPE</td>
<td>Surface Cleaning of Optics by Plasma Exposure (U.S.)</td>
</tr>
<tr>
<td>SEM</td>
<td>scanning electron microscopy</td>
</tr>
<tr>
<td>SHG</td>
<td>second-harmonic generator</td>
</tr>
<tr>
<td>SHM</td>
<td>screened hydrogenic model</td>
</tr>
<tr>
<td>SIMS</td>
<td>secondary-ion mass spectroscopy</td>
</tr>
<tr>
<td>slm</td>
<td>standard liters per minute</td>
</tr>
<tr>
<td>SOSA</td>
<td>spin-orbit split array</td>
</tr>
<tr>
<td>SPF</td>
<td>spectral purity filter</td>
</tr>
<tr>
<td>SRC</td>
<td>Semiconductor Research Corporation (U.S.)</td>
</tr>
<tr>
<td>SRIM</td>
<td>Stopping and Range of Ions in Matter</td>
</tr>
<tr>
<td>STA</td>
<td>supertransition array</td>
</tr>
<tr>
<td>STE</td>
<td>self-trapped exciton</td>
</tr>
<tr>
<td>STM</td>
<td>scanning tunneling microscope</td>
</tr>
<tr>
<td>SURF II</td>
<td>Synchrotron Ultraviolet Radiation Facility (at NIST)</td>
</tr>
<tr>
<td>TBD</td>
<td>to be determined</td>
</tr>
<tr>
<td>TDLDA</td>
<td>time-dependent local density approximation</td>
</tr>
<tr>
<td>TE</td>
<td>thermal equilibrium</td>
</tr>
<tr>
<td>TEM</td>
<td>transmission electron microscopy</td>
</tr>
<tr>
<td>TF</td>
<td>Thomas-Fermi</td>
</tr>
<tr>
<td>TGS</td>
<td>transmission grating spectrograph</td>
</tr>
<tr>
<td>TMP</td>
<td>turbomolecular pump</td>
</tr>
<tr>
<td>TOF</td>
<td>time-of-flight</td>
</tr>
<tr>
<td>TPS</td>
<td>Thomson parabola spectrometer</td>
</tr>
<tr>
<td>TRINITI</td>
<td>Troitsk Institute of Innovation and Fusion Research (Russia)</td>
</tr>
<tr>
<td>TRIM</td>
<td>Transport of Ions in Matter</td>
</tr>
<tr>
<td>TVD</td>
<td>total variation diminishing</td>
</tr>
<tr>
<td>TWG</td>
<td>Technical Working Group</td>
</tr>
<tr>
<td>UHV</td>
<td>ultrahigh vacuum</td>
</tr>
<tr>
<td>UTA</td>
<td>unresolved transition array</td>
</tr>
<tr>
<td>VNL</td>
<td>Virtual National Laboratory (U.S.)</td>
</tr>
<tr>
<td>VUV</td>
<td>vacuum ultraviolet</td>
</tr>
<tr>
<td>WDS</td>
<td>wafer dose sensor</td>
</tr>
<tr>
<td>WS</td>
<td>working standard</td>
</tr>
<tr>
<td>XPS</td>
<td>x-ray photoelectron spectroscopy</td>
</tr>
</tbody>
</table>