X-Rays From Laser Plasmas

Generation and Applications

I. C. E. TURCU

CLRC Rutherford Appleton Laboratory, UK

and

J. B. DANCE
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foreword</td>
<td>xv</td>
</tr>
<tr>
<td>Preface</td>
<td>xvii</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>xix</td>
</tr>
<tr>
<td>1 Introduction</td>
<td>1</td>
</tr>
<tr>
<td><strong>PART I Physical Principles</strong></td>
<td></td>
</tr>
<tr>
<td>2 Interaction of Soft X-Rays with Matter: Wave Behaviour ($\lambda \sim 1$ nm)</td>
<td></td>
</tr>
<tr>
<td>2.1 Proximity X-Ray Lithography for the Semiconductor Industry</td>
<td>7</td>
</tr>
<tr>
<td>2.1.1 Resolution limits</td>
<td>8</td>
</tr>
<tr>
<td>2.1.2 Road map for the semiconductor industry in the</td>
<td>10</td>
</tr>
<tr>
<td>twenty-first century</td>
<td></td>
</tr>
<tr>
<td>2.1.3 Comparison between optical and X-ray lithography</td>
<td>12</td>
</tr>
<tr>
<td>2.1.4 Exposure geometry for proximity X-ray lithography</td>
<td>15</td>
</tr>
<tr>
<td>2.1.5 Radiation sources for 1 nm X-ray lithography</td>
<td>18</td>
</tr>
<tr>
<td>2.1.5.1 Comparison of point X-ray sources</td>
<td>19</td>
</tr>
<tr>
<td>2.1.5.2 Specification of the laser plasma X-ray source for</td>
<td>21</td>
</tr>
<tr>
<td>lithography</td>
<td></td>
</tr>
<tr>
<td>2.1.6 Resolution and throughput of X-ray lithography using</td>
<td>22</td>
</tr>
<tr>
<td>point sources</td>
<td></td>
</tr>
<tr>
<td>2.1.7 Deep X-ray lithography for micromachining</td>
<td>25</td>
</tr>
<tr>
<td>2.1.7.1 The LIGA method</td>
<td>26</td>
</tr>
<tr>
<td>2.1.7.2 Fast-exposure LIGA for 1 nm X-rays</td>
<td>28</td>
</tr>
<tr>
<td>2.2 Contact X-Ray Microscopy</td>
<td>30</td>
</tr>
<tr>
<td>2.2.1 Exposure cell for 'water window' X-rays</td>
<td>31</td>
</tr>
<tr>
<td>2.2.2 Comparison between electron, optical and X-ray microscopes</td>
<td>32</td>
</tr>
<tr>
<td>2.2.3 Resolution limit</td>
<td>33</td>
</tr>
<tr>
<td>2.2.4 Future improvements</td>
<td>34</td>
</tr>
<tr>
<td>2.3 Coherent, Point-like Plasma X-Ray Sources</td>
<td>35</td>
</tr>
<tr>
<td>2.3.1 Coherence condition</td>
<td>35</td>
</tr>
<tr>
<td>2.3.2 Coherence measurements: Young's double-slit experiment</td>
<td>38</td>
</tr>
<tr>
<td>2.3.3 Temporal coherence</td>
<td>41</td>
</tr>
<tr>
<td>2.3.4 Coherent source for 0.834 nm X-rays</td>
<td>42</td>
</tr>
<tr>
<td>2.4 X-Ray Holography</td>
<td>43</td>
</tr>
</tbody>
</table>
## Contents

2.4.1 Gabor in-line geometry 44  
2.4.2 Fourier transform geometry 45  
2.4.3 Gabor hologram recorded with 0.834 nm X-rays 46  
  2.4.3.1 Hologram recording 46  
  2.4.3.2 Hologram reconstruction 48  

2.5 Zone Plate X-Ray Lens 50  
  2.5.1 Focal length of zone plate optics 50  
  2.5.2 Resolution and efficiency of zone plate optics 52  
  2.5.3 Imaging transmission X-ray microscope 53  
  2.5.4 Scanning transmission X-ray microscope (STXM) 55  
    2.5.4.1 STXM construction and operation 56  
    2.5.4.2 STXM resolution 58  
    2.5.4.3 High-resolution images of chromosomes 59  
    2.5.4.4 Laser plasma X-ray source for STXM 60  

2.6 Grazing Incidence Grating X-Ray Spectrographs 61  
  2.6.1 The grating equation 61  
  2.6.2 Carbon plasma X-ray spectrum from Rowland circle spectrometer 63  
  2.6.3 Laser plasma XUV spectra using a flat-field spectrometer 64  
  2.6.4 Laser plasma VUV spectra using a near-normal incidence spectrometer 66  
    2.6.4.1 VUV beamline for the plasma source 66  
    2.6.4.2 Continuously tunable VUV beamline 68  

2.7 Transmission X-Ray Gratings 69  
  2.7.1 Diffraction geometry 69  
  2.7.2 Carbon plasma X-ray spectrum 71  

2.8 X-Ray Crystal Spectrograph 72  
  2.8.1 Bragg condition 72  
  2.8.2 Properties of X-ray dispersive crystals 73  
  2.8.3 Crystal X-ray minispectrometer 73  
  2.8.4 Iron plasma X-ray spectra 73  

2.9 Lens-less Imaging: X-Ray Pinhole Camera 76  
  2.9.1 Imaging geometry 76  
  2.9.2 X-ray images of copper plasma 77  
  2.9.3 Space-resolved carbon plasma X-ray spectrum 77  

2.10 Grazing Incidence X-Ray Reflection: The Critical Angle 78  

2.11 Microchannel Plate (MCP) X-Ray Optics 82  
  2.11.1 Focusing geometry for the flat MCP 82  
  2.11.2 MCP X-ray beamline for the plasma source 83  
  2.11.3 Microchannel plate (MCP) collimating optics for X-ray lithography 86  
    2.11.3.1 Collimating geometry of slumped MCP 87  
    2.11.3.2 Throughput-optimized MCP collimator for X-ray lithography 89  
    2.11.3.3 MCP collimated X-ray source for the mass production of microchips 92  

References 93
3 Interaction of Soft X-rays with Matter: Particle Behaviour ($h\nu \sim 1$ keV) 97
  3.1 Photoelectron Generation 97
  3.2 The Vacuum X-Ray Diode 101
    3.2.1 The X-ray streak camera 102
  3.3 The p-i-n X-Ray Diode 104
    3.3.1 Sensitivity 105
    3.3.2 Linearity 107
  3.4 Photographic Film for Soft X-Rays 109
  3.5 Absorption of Soft X-Rays in Matter 110
  3.6 X-Ray Filters 112
    3.6.1 Vanadium bandpass filter for 'water window' X-rays 113
    3.6.2 X-ray filters for proximity lithography 114
  3.7 Soft X-Ray Absorption in Macromolecules 116
    3.7.1 Soft X-ray absorption in photoresist material 116
      3.7.1.1 PMMA photoresist 117
      3.7.1.2 AZ PF514 chemically amplified photoresist 119
      3.7.1.3 EBR9 photoresist 121
    3.7.2 Soft X-ray absorption in biological cells: DNA damage 121
      3.7.2.1 Monolayers of V79 mammalian cells 122
      3.7.2.2 Calculation of X-ray dose 124
      3.7.2.3 DNA damage by soft X-rays 127

References 129

4 Laser-Produced Plasmas 131
  4.1 Absorption of Laser Light in a Plasma 131
  4.2 Black-Body Radiation 138
  4.3 Emission of Electromagnetic Radiation from Laser-Produced Plasmas 139
    4.3.1 Spectral line broadening 141
    4.3.2 Copper plasma emission 142
  4.4 Plasma Equilibrium Models 142
    4.4.1 Collisional–radiative equilibrium (CRE) model 144
    4.4.2 Local thermodynamic equilibrium (LTE) model 149
    4.4.3 Corona equilibrium (CE) model 149
  4.5 Numerical Simulations of Carbon and Aluminium Plasma Emissions 150
    4.5.1 Theoretical model 151
    4.5.2 Simulation results: plasma parameters 151
    4.5.3 Simulation results: emission spectra 153
  4.6 Measurements of Laser-Produced Plasma Parameters by Other Laboratories 158
    4.6.1 Plasma temperature, ablation pressure and mass ablation rate 158
    4.6.2 X-ray emission spectra 160
    4.6.3 Laser to X-ray energy conversion efficiency 163

References 166

Bibliography 168
## Contents

### 5 Excimer Lasers
5.1 Why Use Excimer Laser for Plasma Generation? 169
5.2 Physics of Excimer Lasers 170
  5.2.1 The KrF laser transition 172
  5.2.2 KrF laser bandwidth: amplification of picosecond pulses 173
  5.2.3 Optical materials for high peak power UV laser pulses 175
  5.2.4 Important KrF excimer laser parameters 176
    5.2.4.1 Gain and saturation 176
    5.2.4.2 Laser energy storage time 179
5.3 Short Pulse Energy Extraction from Excimer Amplifiers 180
  5.3.1 Laser energy extraction in trains of short laser pulses 181
5.4 Laser Beam Quality 182
5.5 High Average and Peak Power Commercial Excimer Lasers 182
  5.5.1 Types of commercial excimer lasers 183
  5.5.2 The LPX210i excimer laser 184

### References 187

### PART II X-ray Source Construction, Performance and Applications

### 6 High Power KrF Lasers for X-Ray Generation 191
6.1 Nanosecond KrF Excimer Laser Plasma X-Ray Source 192
  6.1.1 Sprite e-beam pumped laser system 192
  6.1.2 Laser systems using 20 ns discharge-excited excimers 193
    6.1.2.1 Power oscillator–power amplifier laser system 193
    6.1.2.2 Injection-locked unstable resonator amplifier 193
6.2 Picosecond Pulse-Train KrF Excimer System for a Plasma X-Ray Source 196
  6.2.1 Pulse-train ps laser oscillator and power amplifier 197
6.3 Laser System Generating a 150 ps Pulse-Train 199
  6.3.1 Quenched dye laser oscillator 199
  6.3.2 ‘Active etalon’ dye laser amplifier for generating ps pulse-trains 199
  6.3.3 Excimer ps laser power amplifier 200
6.4 Excimer System Producing 7 ps Pulses 201
  6.4.1 Description of laser system 201
  6.4.2 Laboratory-sized laser plasma X-ray source 203
  6.4.3 Generation and amplification of trains of ps pulses 203
  6.4.4 High average power ps excimer laser 204
  6.4.5 Optimization of ps excimer pulse energy 206
6.5 Scaling of ps Excimer Systems to kW Average Power 206
  6.5.1 Parallel excimer final amplifiers 207
  6.5.2 Single kW excimer final amplifier 207

### References 208

### 7 High-Power Laser Plasma X-Ray Source 212
7.1 X-Ray Target Chamber Optimization 212
  7.1.1 Laser beam focusing system 212
7.1.2 X-ray beamlines 214
7.1.3 X-ray chamber construction 215

7.2 Towards a Debris-Free Plasma X-Ray Source 215
7.2.1 KrF laser breakdown in gases 216
7.2.2 X-Ray emission from copper targets in helium at atmospheric pressure 218
7.2.3 Reduction of target debris by the buffer gas
  7.2.3.1 Atomic debris 219
  7.2.3.2 Cluster debris 221
7.2.4 Wafer exposure without target debris contamination 223

7.3 Laser to X-Ray Conversion Efficiency Optimization 223

7.4 X-Ray Conversion Efficiency from Long Laser Pulses 224
7.4.1 Angular distribution of X-ray emission 226
7.4.2 Laser focusing conditions 227
7.4.3 X-ray conversion efficiency measurements 228
7.4.4 Discussion 231
7.4.5 ‘Water window’ X-ray conversion efficiency 232

7.5 Nanosecond Source Delivers 16 mW Average X-Ray Power at 1.4 nm Wavelength 233

7.6 150 ps Pulse-Train Plasma Source Generates 40 mW X-Ray Average Power at 1 nm Wavelength 234

7.7 X-Ray Conversion Efficiency Using 4 ps Excimer Laser Pulses 235
7.7.1 Plasma temperature and density 235
7.7.2 Maximum conversion efficiency to 1 nm X-rays 237
7.7.3 Comparison with other work 238
7.7.4 Parameters affecting the keV X-ray conversion efficiency 239

7.8 X-Ray Average Power of 1 W from a 7 ps Pulse-Train Excimer Laser 241
7.8.1 The concept 242
7.8.2 X-ray average power output 242

7.9 Scaling Laws for X-Ray Average Power 243

7.10 Spatial Properties of the X-Ray Source 244

7.11 Temporal Properties of the X-Ray Source 246

7.12 X-Ray Source Spectral Brightness at 3.37 nm Wavelength 248
7.12.1 Plasma source parameters affecting the spectral brightness 249
7.12.2 Spectral brightness evaluation
  7.12.2.1 Photon flux 251
  7.12.2.2 Bandwidth 251
  7.12.2.3 Efficient source monochromatization 252
  7.12.2.4 X-ray source size and angular emission 254
7.12.3 Comparison with other X-ray sources 254
7.12.4 Spectral brightness scaling 255
7.12.5 Peak spectral brightness 255

7.13 X-Ray Source Coherence 256
7.13.1 Evaluation of plasma source coherence 256
7.13.2 Spatial coherence measurements 257
7.13.3 Temporal coherence 259
## Contents

7.13.4 Discussion and scaling 259  
References 260  
Bibliography 262  

8 X-Ray Microscopy 263  
8.1 Holographic X-Ray Microscopy 263  
8.1.1 X-ray beamline for coherent 'water window' X-rays 263  
8.1.2 Hologram recording 265  
8.1.3 Hologram reconstruction 267  
8.1.4 Future work 267  
8.2 Scanning X-Ray Microscopy 269  
8.2.1 Optimization of the plasma source 269  
8.2.2 Scanning X-ray microscope illuminated by a plasma source 272  
8.2.3 Scanning X-ray microscope images 273  
8.2.4 Scaling 273  
References 275  

9 X-Ray Micro- and Nano-Engineering 276  
9.1 Optimization of Plasma Radiation Source for Lithography Beamlines 276  
9.2 Early Work 278  
9.3 Fabrication of 180 nm FET Gates 278  
9.3.1 Wafer exposure cell 279  
9.3.2 X-ray lithographic exposure and wafer processing 280  
9.3.3 Wafer alignment 281  
9.3.4 Lithography of the 180 nm transistor gate 281  
9.3.5 Transistor performance 283  
9.3.6 Minimization of X-ray exposure time 285  
9.4 Fabrication of Deep, Three-Dimensional Structures by LIGA Technology 285  
9.4.1 Drawbacks of traditional hard X-ray LIGA technique 286  
9.4.2 New soft X-ray LIGA technique 286  
9.4.3 X-ray beamline and exposure cell 286  
9.4.4 Repeated exposure method 287  
9.4.5 Deep, three-dimensional structures 288  
9.4.6 Cavity and waveguide structure for 2.5 THz microwaves 289  
9.4.7 Fast X-ray LIGA for prototyping 280  
References 292  
Bibliography 293  

10 Soft X-Ray Radiobiology 294  
10.1 Ultra-High X-Ray Dose and Dose Rate 294  
10.2 Uniformity of X-Ray Exposure 295  
10.3 X-Ray Exposure at Atmospheric Pressure 296  
10.4 Megarad X-Ray Exposures 296  
10.5 Picosecond X-Ray Exposure 297  
10.6 Interdisciplinary Collaboration 297
## Contents

| 10.7  | Cell Survival Measurements              | 298  |
| 10.8  | DNA Repair Kinetics                    | 299  |
| 10.8.1| X-ray irradiation automation           | 299  |
| 10.8.2| Transient DNA repair rate after X-ray damage | 301  |
| References                                     | 302  |
| 11    | Conclusions                             | 303  |
| Index                                         | 306  |