Debris Characterization And Mitigation Of Droplet Laser Plasma Sources For EUV Lithography

2006

Kazutoshi Takenoshita
University of Central Florida

Find similar works at: http://stars.library.ucf.edu/etd

University of Central Florida Libraries http://library.ucf.edu

Part of the Electrical and Electronics Commons

STARS Citation

Takenoshita, Kazutoshi, "Debris Characterization And Mitigation Of Droplet Laser Plasma Sources For EUV Lithography" (2006). Electronic Theses and Dissertations, 917.
http://stars.library.ucf.edu/etd/917

This Doctoral Dissertation (Open Access) is brought to you for free and open access by STARS. It has been accepted for inclusion in Electronic Theses and Dissertations by an authorized administrator of STARS. For more information, please contact lee.dotson@ucf.edu.
DEBRIS CHARACTERIZATION AND MITIGATION OF
DROPLET LASER PLASMA SOURCES FOR EUV LITHOGRAPHY

by

KAZUTOSHI TAKENOSHITA
Bachelors degree in Electric and Electronic Engineering
Niigata University, Niigata, Japan, 1994
Masters degree in Electric and Electronic Engineering
Niigata University, Niigata, Japan, 1996

A dissertation submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
in the Department of Electrical Engineering
in the School of Electrical Engineering and Computer Science
at the University of Central Florida
Orlando, Florida

Summer Term
2006

Major Professor: Martin C Richardson
ABSTRACT

Extreme ultraviolet lithography (EUVL) is a next generation lithographic techniques under development for fabricating semiconductor devices with feature sizes smaller than 32 nm. The optics to be used in the EUVL steppers is reflective optics with multilayer mirror coatings on each surface. The wavelength of choice is 13.5 nm determined by the optimum reflectivity of the mirror coatings. The light source required for this wavelength is derived from a hot-dense plasma produced by either a gas discharge or a laser. This study concentrate only on the laser produced plasma source because of its advantages of scalability to higher repetition rates.

The design of a the laser plasma EUVL light source consists of a plasma produced from a high-intensity focused laser beam from a solid/liquid target, from which radiation is generated and collected by a large solid angle mirror or array of mirrors. The collector mirrors have the same reflectivity characteristics as the stepper mirrors. The EUVL light source is considered as the combination of both the hot-dense plasma and the collector mirrors.

The EUVL light sources required by the stepper manufacturers must have sufficient EUV output power and long operational lifetimes to meet market-determined chip production rates. The most influential factor in achieving the required EUV output power is the conversion efficiency (CE) of laser input energy relative to the EUV radiation collected. A high CE is demonstrated in a separate research program by colleagues in the Laser Plasma laboratory at CREOL. Another important factor for the light source is the reflectivity lifetime of the collection optics as mirror reflectivity can be degraded by deposition and ablation from the plasma debris. Realization of a high CE but low debris plasma source is possible by
reducing the mass of the target, which is accomplished by using tin-doped droplet targets. These have sufficient numbers of tin atoms for high CE, but the debris generation is minimal.

The first part of this study investigates debris emissions from tin-doped droplet targets, in terms of aerosols and ions. Numerous tin aerosols can be created during a single laser-target interaction. The effects these interactions are observed and the depositions are investigated using SEM, AFM, AES, XPS, and RBS techniques. The generation of aerosols is found to be the result of incomplete ionization of the target material, corresponding to non-optimal laser coupling to the target for maximum CE. In order to determine the threats of the ion emission to the collector mirror coatings from an optimal, fully ionized target, the ion flux is measured at the mirror distance using various techniques. The ion kinetic energy distributions obtained for individual ion species are quantitatively analyzed. Incorporating these distributions with Monte-Carlo simulations provide lifetime estimation of the collector mirror under the effect of ion sputtering. The current estimated lifetime the tin-doped droplet plasma source is only a factor of 500 less than the stepper manufacturer requirements, without the use of any mitigation schemes to stop these ions interacting with the mirror.

The second part of this investigation explores debris mitigation schemes. Two mitigation schemes are applied to tin-doped droplet laser plasmas; electrostatic field mitigation, and a combination of a foil trap with a magnetic field. Both mitigation schemes demonstrate their effectiveness in suppressing aerosols and ion flux. A very small number of high-energy ions still pass through the combination of the two mitigation schemes but the sputtering caused by these ions is too small to offer a threat to mirror lifetime. It is estimated that the lifetime of the collector mirror, and hence the source lifetime, will be sufficient when tin-doped targets are used in combination with these mitigation schemes.
ACKNOWLEDGMENTS

I would like to take a moment to express great appreciations to those who have supported this study. Without them, this study would have never been completed as it is now. I would like to thank first, Dr. Martin Richardson for providing this opportunity, advising this study, and stimulating my scientific and engineering curiosity. I would also like to thank all the committee members for valuable contributions, Dr. Kalpathy Sundaram, Dr. Aravinda Kar, Dr. Donald Malocha for discussing the possibilities of SAW detectors, and Dr. William Silfvast for discussing on the fundamentals of laser plasmas. In addition, I would also like to thank Dr. David Attwood for encouraging me in the EUV research and contributing this thesis.

I am very fortunate to join the Laser Plasma Laboratory where I meet fine scientists and students from all different countries. For the droplet laser plasma generation, Dr. Christian Keyser, and Dr. Chiew-Seng Koay, because of their previous work, this study has its own meaning. I have gained precious help from, as well as a lot of knowledge through discussions with, Ms. Simi George, Mr. Tobias Schmid, Mr. Teddy Peponnet, Mr. Robert Bernath, Mr. Joshua Duncan, Mr. Somsak Teerawattanasook, Mr. Jose Cunado, Ms. Ji-Yeon Choi, and all the colleagues.

I like to thank the people in CREOL who discussed with me in the research, laser plasmas, lasers and optics, especially Dr. Grag Shimkaveg, Dr. Etsuo Fujiwara, Dr. Nikolai Vorobiev, Mr. Isao Matsubara, Dr. Sebastian Gauza, Dr. Fumiyo Yoshino, Dr. Yung-Hsun Wu, and Dr. Yi-Hsin Lin. In addition, there are many scientist outside school gave me valuable inputs in different universities, organizations, and companies, especially Mr Yasuaki Fukuda and Dr.Kazuaki Hotta for explaining the whole picture of the lithography industry.
I have kept a strong desire in my mind towards the application of the droplet generations. It is my turn to contribute to those who worked together in Silver Seiko Ltd. and Siemens-Elema AB, where I have gained all varieties of knowledge and techniques that I can apply throughout the study. I like especially to express my appreciation to Dr. Milan Pokorny for all the initiations and his friendship, Mr. Ulf Fahlström for supporting and his friendship, Dr. Masayuki Muto, Mr. Shizuo Terashima, Mr. Takeshi Fujiwara, Mr. Kunio Takahashi, for giving me the opportunities for the SRjet printing head development.

This study is also a result of all the support I have had from friends and family. Dr. Takeo Maruyama and Mrs. Makiko Maruyama, Mr. Masaki Uesugi, and all the friends in Niigata city and Kashiwazaki city have been supporting and encouraging me and my wife, Miyuki. Dr. Calvin Hayes and Mrs. Barbara Hayes have been encouraging me and believed in me for pursuing this study. My parents and parents-in-law have been very supportive and waiting for me to complete the study. Lastly I thank my wife, Miyuki, for supporting me in here in the states. She should receive my most appreciation.
TABLE OF CONTENTS

LIST OF FIGURES .......................................................... xvii

LIST OF TABLES ........................................................... xviii

LIST OF ACRONYMS/ABBREVIATIONS ................................. xix

CHAPTER 1 INTRODUCTION ............................................. 1
  1.1 EUV Lithography ...................................................... 1
    1.1.1 Overview of EUVL ............................................. 3
    1.1.2 EUVL source requirement ..................................... 4
    1.1.3 Conversion efficiency ....................................... 5
    1.1.4 Source lifetime ............................................... 6
  1.2 EUV - Soft X-ray sources ........................................ 7
    1.2.1 Synchrotron radiation ...................................... 8
    1.2.2 Gas discharge dense plasmas .............................. 9
    1.2.3 Laser plasmas ................................................. 10
  1.3 Multilayer mirror coating and reflectivity ..................... 12
    1.3.1 Absorption of soft X-ray in materials ................... 12
    1.3.2 Reflectivity of multi-layer mirror ....................... 13
  1.4 Summary of background and motivation ......................... 15

CHAPTER 2 LASER PLASMAS AND DEBRIS ............................ 17
  2.1 Introduction ....................................................... 17
2.1.1 Laser Plasma generation ........................................ 18
2.1.2 Absorption of laser energy in fully ionized plasmas ......... 18
2.1.3 Ionization stages ............................................ 20
2.1.4 Fluid descriptions of laser plasmas .......................... 23
2.1.5 Plasma expansion ........................................... 25
2.1.6 Recombination ............................................... 26
2.2 Debris generation ................................................ 26
  2.2.1 Solid target and debris .................................... 27
  2.2.2 Hot rocks and aerosols .................................... 28
  2.2.3 Ions, electrons, and neutral atoms ........................ 29
2.3 Mass-limited target ............................................ 30
  2.3.1 Different target configurations ............................. 30
  2.3.2 Number of atoms in a target ............................... 32
2.4 Summary of laser plasmas and debris generation ............... 34

CHAPTER 3  MULTILAYER MIRROR REFLECTIVITY DEGRADATION  35
3.1 Introduction ..................................................... 35
3.2 Deposition ...................................................... 35
  3.2.1 EUV absorption of target materials ........................ 36
  3.2.2 Absorption estimates of thin film .......................... 37
  3.2.3 Oxidation of multi-layer mirror surfaces .................... 39
  3.2.4 Absorption of an oxide layers ............................. 39
  3.2.5 Photon induced oxidation processes ........................ 40
  3.2.6 Impact on oxidation on collector mirror surfaces .......... 41
3.3 Erosion on multi-layer surfaces .............................. 43
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>Introduction</td>
<td>68</td>
</tr>
<tr>
<td>5.2</td>
<td>Aerosol deposition on witness plates</td>
<td>68</td>
</tr>
<tr>
<td>5.2.1</td>
<td>Identification of the deposits</td>
<td>69</td>
</tr>
<tr>
<td>5.2.2</td>
<td>Profile measurement of the deposits</td>
<td>71</td>
</tr>
<tr>
<td>5.2.3</td>
<td>Aerosol flux calculation</td>
<td>72</td>
</tr>
<tr>
<td>5.3</td>
<td>Aerosol generation processes</td>
<td>74</td>
</tr>
<tr>
<td>5.3.1</td>
<td>Aerosol generation in low intensity laser irradiation</td>
<td>74</td>
</tr>
<tr>
<td>5.3.2</td>
<td>Origin of aerosol generation</td>
<td>75</td>
</tr>
<tr>
<td>5.3.3</td>
<td>Laser energy, intensity, focus diameter</td>
<td>77</td>
</tr>
<tr>
<td>5.3.4</td>
<td>Total tin atom emission</td>
<td>78</td>
</tr>
<tr>
<td>5.4</td>
<td>Summary of particulate debris</td>
<td>79</td>
</tr>
<tr>
<td>6.1</td>
<td>Introduction</td>
<td>80</td>
</tr>
<tr>
<td>6.2</td>
<td>Ion emission characteristics</td>
<td>80</td>
</tr>
<tr>
<td>6.2.1</td>
<td>Ion flux measurement</td>
<td>81</td>
</tr>
<tr>
<td>6.2.2</td>
<td>Mass spectrometer</td>
<td>82</td>
</tr>
<tr>
<td>6.2.3</td>
<td>Quantitative ion spectrometer analysis</td>
<td>84</td>
</tr>
<tr>
<td>6.2.4</td>
<td>Emission dependency on the laser intensities</td>
<td>91</td>
</tr>
<tr>
<td>6.3</td>
<td>Erosion study</td>
<td>95</td>
</tr>
<tr>
<td>6.3.1</td>
<td>Limitation of laser repetition rate</td>
<td>95</td>
</tr>
<tr>
<td>6.3.2</td>
<td>Lifetime estimation of mirror reflectivity degradation</td>
<td>96</td>
</tr>
<tr>
<td>6.4</td>
<td>Plasma expansion simulation</td>
<td>98</td>
</tr>
<tr>
<td>6.4.1</td>
<td>Simplified model of fluid simulations</td>
<td>99</td>
</tr>
<tr>
<td>6.4.2</td>
<td>MEDUSA plasma expansion simulations</td>
<td>101</td>
</tr>
</tbody>
</table>
6.4.3 Comparison between simulations and ion measurements . . . . . . . 106
6.5 Summary of ion emission characteristics . . . . . . . . . . . . . . . . . 111

CHAPTER 7 MITIGATION . . . . . . . . . . . . . . . . . . . . . . . . . . . 112
7.1 Introduction . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 112
  7.1.1 Types of mitigation schemes . . . . . . . . . . . . . . . . . . . . . 112
7.2 Repeller field mitigation . . . . . . . . . . . . . . . . . . . . . . . . . . . 113
  7.2.1 Effectiveness of repeller field on ion flux . . . . . . . . . . . . . . . 114
  7.2.2 Effectiveness of repeller field on aerosols . . . . . . . . . . . . . . . 118
7.3 Magnetic foil trap mitigation . . . . . . . . . . . . . . . . . . . . . . . . . 120
  7.3.1 Particle motion in the magnetic field and foil structures . . . . . . . 121
  7.3.2 Particle motion in non-uniform magnetic field . . . . . . . . . . . . . 126
  7.3.3 Effectiveness of foil trap mitigation . . . . . . . . . . . . . . . . . . 127
7.4 Combination of two mitigation schemes . . . . . . . . . . . . . . . . . . . . 129
  7.4.1 Detection limit of ion flux . . . . . . . . . . . . . . . . . . . . . . . . 130
  7.4.2 Demonstration of sufficient ion flux reduction . . . . . . . . . . . . . 133
  7.4.3 Neutral atom mitigation . . . . . . . . . . . . . . . . . . . . . . . . . 134
7.5 Summary of mitigation . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 134

CHAPTER 8 CONCLUSION AND FUTURE WORK . . . . . . . . . . . . . . . . . . . . 136
8.1 Conclusion . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 136
8.2 Future work . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 137
  8.2.1 High repetition rate laser plasmas . . . . . . . . . . . . . . . . . . . . 137
  8.2.2 Target stabilization systems . . . . . . . . . . . . . . . . . . . . . . . 138
  8.2.3 Radiation study under magnetic field existence . . . . . . . . . . . . . 138
LIST OF FIGURES

1.1 A general schematic of optical component layout of EUVL stepper machines [9]. .................................................. 4
1.2 Schematic of synchrotron radiation [16]. .............................................. 9
1.3 Schematic of gas discharge plasma source configuration [21]. ............. 10
1.4 An example of laser plasma EUV source, mirror, and IF configuration [22]. 11
1.5 TEM cross section image of Mo/Si multilayer mirror surface [24]. ........ 14
1.6 Reflectivity characteristics of Si/Mo multilayer coatings [25]. ............... 15

2.1 Ionization rate calculation at different electron densities. .................... 22
2.2 Population of tin ion species as function of electron temperature. .......... 23
2.3 Comparison of multilayer mirror surfaces exposed by Li and Sn plasmas [47]. 29

3.1 Absorption coefficient of Li, Sn, and Xe. ......................................... 37
3.2 Transmission of thin film 10 nm of Si, Nb, Ru, Li, and Sn [25]. .............. 38
3.3 Transmission of oxide layers [25]. ................................................. 40
3.4 Mirror reflectivity degradation characteristics measured [66]. .............. 42
3.5 SEM image of a multilayer mirror surface showing the evidence of the erosion caused by high energy oxygen ions [76]. .................................... 44
3.6 Si/Mo multilayer mirror reflectivity characteristics of different number of bi-layers [25]. ......................................................... 46

4.1 Photo of the laser system ............................................................... 49
4.2 Photo of target chamber ............................................................... 50
4.3 Schematic of optical setting on the target chamber ........................................ 51
4.4 Orientations of target delivery, cold trap, heating laser pulse, imaging system, and a visible image of the plasma observed by the imaging system. ........ 53
4.5 Timing diagram of droplet and laser synchronization ................................. 54
4.6 Experimental setup for (top) witness plate and (bottom) sample holder ... 56
4.7 Schematic of Faraday cup ion probe .......................................................... 58
4.8 Schematic of (ESIEA) ion spectrometer ................................................... 59
4.9 (a) Schematic of TPS, (b) Ion signals measured by TPS ......................... 61
4.10 Schematic of amplified ion probe ............................................................ 62
4.11 Concept of repeller field mitigation ......................................................... 63
4.12 IP, ESIEA measurements with the repeller field, and witness plate measurement with the repeller field. ................................................................. 64
4.13 Schematic of magnetic foil trap single channel experiment ..................... 66
4.14 Photos of magnetic foil trap single channel experiment setup (left) the magnetic core, (right) single channel foil. ................................................. 66
5.1 (a) Auger electron spectrum taken from the witness plate and (b) X-ray photoelectron spectrum taken from the same plate sample. .............. 70
5.2 AES Sn signal comparison on the deposited aerosol. .............................. 71
5.3 AFM image of tin deposition on a multilayer mirror. ............................... 72
5.4 Deposit volume dependency of the diameters. ......................................... 73
5.5 (a) AES image 140µm X 140µm, (b) Back-scattered image (Same area). . . . 74
5.6 (a) distances of target, mask, and witness plate, (b) dark field image of the witness plate surface. ................................................................. 76
5.7 (a) SEM image of witness plate surface exposed by plasma created by 30 mJ laser pulse, (b) by 120 mJ pulse.

6.1 Ion probe signals measured at 150mm from the plasma.

6.2 Ion probe signal from solid tin planer target.

6.3 (a) Ion spectrum and ion probe signal from water droplet target, (b) Ion spectrum and ion probe signal from Tin 30% doped droplet target.

6.4 (a) Typical ESIEA signal, (b) converted M/Z signal.

6.5 (a) Collected M/Z signals, (b) interpolated M/Z spectral map.

6.6 Detailed schematics of ESIEA for quantitative analysis.

6.7 Tin ions energy distributions at intensity of $9.7 \times 10^{10}$ W/cm$^2$.

6.8 Ion probe signals at different laser intensities at 125 mm distance from the plasma.

6.9 Ion kinetic energy distributions of (a) O+, (b) O$^{2+}$, (c), and O$^{5+}$.

6.10 Ion kinetic energy distributions of (a) Sn+, (b) Sn$^{2+}$, (c), and Sn$^{5+}$.

6.11 The incident ion energy dependencies of the sputtering yields for Si, Mo surfaces. (SRIM calculations)

6.12 Concept of cells and properties of the simplified fluid model.

6.13 Electron density and temperature profiles calculated by the simplified fluid model at 2 ns of 10 ns, 100 mJ Gaussian laser pulse.

6.14 Medusa calculations of electron density and temperature transient at laser intensity of $1.0 \times 10^{11}$ W/cm$^2$.

6.15 Medusa calculations of electron density and temperature transient at laser intensity of $2.0 \times 10^{11}$ W/cm$^2$. 
6.16 Medusa calculations of electron density and temperature transient at laser intensity of $3.0 \times 10^{11}$ W/cm$^2$. .......................................................... 105
6.17 Comparisons of ion probe signal and electron density transient at (a) intensity of $2.0 \times 10^{11}$ W/cm$^2$, (b) $3.0 \times 10^{11}$W/cm$^2$. .................................................. 107
6.18 Reconstructed ion signals of total signals and individual elements at laser intensities of (a) $1.9 \times 10^{11}$, (b) $2.8 \times 10^{11}$ W/cm$^2$. ................................. 109
6.19 Reconstructed ion signals at laser intensities of $2.8 \times 10^{11}$ W/cm$^2$. (a) Oxygen ions, and (b) tin ions ................................................................. 110

7.1 Comparison of IP signals with repeller field and without the field. ........... 115
7.2 Ion M/Z spectral analysis on the repeller field effectiveness. ................. 117
7.3 (a) Secondary electron image of $50 \mu$m x $50 \mu$m of surface exposed without the repeller field, (b) Secondary electron image of $50 \mu$m x $50 \mu$m of surface exposed with the repeller field, (c) Auger electron tin elemental mapping of the same area as (a), (d) Tin elemental mapping of the same area as (b). . . . 119
7.4 An example of the magnetic foil trap configuration. ................................. 120
7.5 Relationships between $\Phi$ and $R$ under a uniform magnetic field. ........... 124
7.6 The illustration of the critical ion trajectory and foils.............................. 124
7.7 Ion deflection rates of (a) tin ion species under uniform magnetic field of 0.1 T (b) different ion species under uniform magnetic field of 0.1 T (c) Sn$^+$ under different magnetic field. ......................................................... 125
7.8 Measured magnetic field profile on foil channel plane............................. 127
7.9 IP measurement with magnetic foil trap for (a) water droplet target case, (b) tin-doped droplet target case. ......................................................... 128
7.10 Photo and schematic of modified encapsulated repeller field mitigation. . . 130
7.11 IP signal comparison between different field potentials of the modified Repeller Field. ................................................................. 132
7.12 IP signals on the modified Magnetic Foil Trap. ................................. 132
7.13 Amplified ion probe signals with two mitigation schemes installed. .... 133

A.1 Ion energy distributions of Hydrogen ions. .................................... 142
A.2 Ion energy distributions of different Oxygen ions. .......................... 143
A.3 Ion energy distributions of different Chlorine ions. .......................... 144
A.4 Ion energy distributions of different Tin ions. ................................ 145
LIST OF TABLES

1.1 Table 1 EUVL source requirements [12]................. 5
# LIST OF ACRONYMS/ABBREVIATIONS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EUV</td>
<td>Extreme ultraviolet</td>
</tr>
<tr>
<td>EUVL</td>
<td>Extreme ultraviolet lithography</td>
</tr>
<tr>
<td>OPC</td>
<td>Optical proximity correction technique</td>
</tr>
<tr>
<td>NA</td>
<td>Numerical aperture</td>
</tr>
<tr>
<td>IF</td>
<td>Intermediate focus</td>
</tr>
<tr>
<td>CE</td>
<td>Conversion efficiency</td>
</tr>
<tr>
<td>MLM</td>
<td>Multilayer mirror</td>
</tr>
<tr>
<td>BW</td>
<td>Bandwidth</td>
</tr>
<tr>
<td>EM</td>
<td>Electro-magnetic</td>
</tr>
<tr>
<td>CXRO</td>
<td>Center for X-ray optics</td>
</tr>
<tr>
<td>IBA</td>
<td>Inverse Bremsstrahlung absorption</td>
</tr>
<tr>
<td>LTE</td>
<td>Local thermal equilibrium</td>
</tr>
<tr>
<td>PLD</td>
<td>Pulsed laser deposition</td>
</tr>
<tr>
<td>ETS</td>
<td>Engineering test stand</td>
</tr>
<tr>
<td>SRIM</td>
<td>Stopping and range of ions in matter</td>
</tr>
<tr>
<td>YAG</td>
<td>Yttrium aluminum garnet</td>
</tr>
<tr>
<td>PLL</td>
<td>Phase lock loop</td>
</tr>
<tr>
<td>IP</td>
<td>Ion probe</td>
</tr>
<tr>
<td>TOF</td>
<td>Time of flight</td>
</tr>
<tr>
<td>ESIEA</td>
<td>Electrostatic ion energy analyzer</td>
</tr>
<tr>
<td>CEM</td>
<td>Channel electron multiplier</td>
</tr>
<tr>
<td>KE</td>
<td>Kinetic energy</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>------------------------------------------------</td>
</tr>
<tr>
<td>TPS</td>
<td>Thomson parabola spectrometer</td>
</tr>
<tr>
<td>MCP</td>
<td>Microchannel plate</td>
</tr>
<tr>
<td>QCM</td>
<td>Quartz crystal microbalance</td>
</tr>
<tr>
<td>SAW</td>
<td>Surface acoustic wave</td>
</tr>
<tr>
<td>AES</td>
<td>Auger electron spectroscopy</td>
</tr>
<tr>
<td>XPS</td>
<td>X-ray photon spectroscopy</td>
</tr>
<tr>
<td>RBS</td>
<td>Rutherford backscattering spectroscopy</td>
</tr>
<tr>
<td>AFM</td>
<td>Atomic force microscopy</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning electron microscopy</td>
</tr>
<tr>
<td>TEM</td>
<td>Transmission electron microscopy</td>
</tr>
<tr>
<td>OM</td>
<td>Optical microscopy</td>
</tr>
<tr>
<td>CVD</td>
<td>Chemical vapor deposition</td>
</tr>
<tr>
<td>MFT</td>
<td>Magnetic foil trap mitigation</td>
</tr>
</tbody>
</table>
CHAPTER 1
INTRODUCTION

1.1 EUV Lithography

The lithographic technique for semiconductor chip fabrication has progressively advanced over the last 35 years in terms of the integration, complexity, throughput and productivity. In fact, although the number of transistors on a single chip has increased by nearly a million times over this time period, the price of the chip has remained almost constant. The key to this advancement is the minimum feature size of the fabrication processes. The number of transistors incorporated into a microchip can depend on the chip size and the minimum feature size and further advancements in semiconductor devices will require even smaller feature sizes. The minimum feature size is determined by a modification of the Rayleigh equation [1],

\[ W = k_1 \frac{\lambda}{NA} \]  

(1.1)

where \( k_1 \) is a constant determined by the many factors involved in the lithographic technique, \( NA \) is the numerical aperture of the illuminating optics, and \( \lambda \) is the wavelength of the light source. The minimum value of \( k_1 \) is 0.25 for a single exposure process. Unfortunately the production yield decreases as \( k_1 \) approaches this minimum value. The maximum achievable value of \( NA \) is 1.0 for atmospheric environments.

The semiconductor industry has already pushed the \( k_1 \) factor and \( NA \) close to their physical limits in order to decrease the minimum feature size. Beginning with visible light sources, the wavelength of the light source has now been reduced to the UV range, specifically
193 nm, and to continue to reduce the minimum feature size even more, shorter wavelength light will be required. Other options under consideration to reduce the minimum feature size are the immersion lithographic technique [2], double exposure technique [3], and optical proximity correction technique [4] (OPC). The immersion lithography utilizes water or another fluid with a high refractive index between the photoresist on the wafer and the closest optical component to the resist. The fluid allows a higher $NA$ than unity which reduces the minimum feature size. The double exposure technique requires two different masks and exposure processes for each wafer exposure allowing a reduction of the $k_1$ factor smaller than 0.25, thereby reducing the feature size. The OPC technique is applied in the mask design phase with the defect processes of the printed image of the mask. The design process tends to be more complex but it is implemented in the design software [5]. The OPC does not reduce the minimum feature size directly but it increases the product yields so that the process can approach the physical limit where the choice of the feature size becomes practical with the improved productivity.

EUV lithography (EUVL) utilizes a light source radiation at 13.5 nm. At this wavelength the $\lambda$ in Equation 1.1 is more than an order of magnitude smaller than the wavelength used in current techniques. Thus the tolerances for the $NA$ and $k_1$ factor can be more relaxed using the shorter wavelength radiation. The $NA$ for EUVL is 0.25, and the $k_1$ factor is approximately 0.6. EUVL is expected to fabricate semiconductor products with feature sizes of 32 nm and smaller [6], extending the lifetime of Moore’s Law evolution of chip manufacture for perhaps another 20 years. However, many technological challenges remain in order for EUVL to be implemented into the device fabrication process. Thus there are many research areas and activities to overcome those challenges. Due to the increasing research and development cost for the new generation lithography, the leading research groups share their
future perspectives and strategies. A number of conferences and workshops are conducted each year to share their progress, to discuss technologies involved, and to identify critical issues [7]. It was recently reported that immersion lithography will be inserted between the current lithographic technique and EUVL to achieve 32 nm [8]. EUVL is expected to be implemented for printing 22 nm nodes in 2011.

1.1.1 Overview of EUVL

Like conventional lithographic techniques, EUVL systems consist of a light source, collection optics, illumination optics, a mask, projection optics, and a photoresist on a Si wafer surface. A general schematic of the component layout is illustrated in Figure 1.1 [9]. The EUV radiation is generated at the source and is transferred to the illumination optics via collection optics. The mask pattern is then reduced and imaged onto the photo resist through the projection optics. The exposure process is then followed by development and other processes that impart designed functionalities in the patterned Si surface [10]. Due to the absorption of EUV radiation by most materials, the exposure process has to be executed in a high vacuum environment. The optical elements in the system are all reflective optics, which exhibit narrow band reflectivity at 13.5 nm. The reflectivity characteristics are determined by the properties of specialized multilayer coatings on a mirror surface substrate [11]. The output of the light source required must supply sufficient radiation into the reflectivity band of the optics. The required source power is determined by the production throughput, transmission of the whole optical system, and photoresist sensitivity.
1.1.2 EUVL source requirement

The EUVL source requirements are determined in terms of power, repetition rate, spectral purity, etendue, and the rest as shown in Table 1.1 [12]. All the requirements are determined based on the values at the intermediate focus (IF) which is the interface between the EUVL source and the illumination optics. Once the characteristics needed for the light source are determined, then all the optical systems can be designed and fabricated separately. It is the light source developer’s responsibility to satisfy all the necessary requirements. The configurations for source development are largely based on either gas discharge plasmas or laser produced plasmas. Both of these are hot dense plasmas generated with short pulses of energy. A number of configurations are used to produce these plasmas and detailed descriptions of the arrangements are summarized in later sections of this chapter.
Table 1.1: Table 1 EUVL source requirements [12].

<table>
<thead>
<tr>
<th>SOURCE CHARACTERISTICS</th>
<th>REQUIREMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>· Wavelength</td>
<td>13.5 [nm]</td>
</tr>
<tr>
<td>· EUV Power (in-band)</td>
<td>115 [W]*</td>
</tr>
<tr>
<td>· Repetition Frequency</td>
<td>&gt; 7-10 kHz ***</td>
</tr>
<tr>
<td>· Integrated Energy Stability</td>
<td>±0.3%, 3σ over 50 pulses</td>
</tr>
<tr>
<td>· Source Cleanliness</td>
<td>≥ 30,000 hours **</td>
</tr>
<tr>
<td>· Etendue of Source Output</td>
<td>max 3.3 mm²sr***</td>
</tr>
<tr>
<td>· Max. solid angle input to illuminator</td>
<td>0.03 - 0.2 [sr] ***</td>
</tr>
<tr>
<td>· Spectral Purity:</td>
<td></td>
</tr>
<tr>
<td>130-400 [nm] (EUV/UV)</td>
<td>≤ 3-7% ***</td>
</tr>
<tr>
<td>≥400 [nm] (IRVis) at Wafer</td>
<td>TBD ***</td>
</tr>
</tbody>
</table>

* At IF
** After IF
*** Design dependent

The most challenging areas to fulfill among the requirements listed are the inband EUV source power and lifetime (listed as source cleanliness). To facilitate the continuous operation of EUVL stepper machines, the light sources need to provide the required power continuously with minimal interruptions, such as for routine maintenance (97% up-time). The source power requirement depends on the desired product throughput, optical throughput of the whole system, exposure field size, and photoresist sensitivity [13]. To achieve the required light source power, the conversion efficiency (CE), the ratio of the energy supplied relative to EUV energy generated in the narrow band, needs to be high. The CE value as well as the source lifetime has been improved by many research groups in recent years.

1.1.3 Conversion efficiency

The conversion efficiency (CE) of useful EUV energy output from supplied input energies is a very important factor in EUVL source development. It limits the maximum
EUV power because input power is limited by the electricity cost and the technological limitation of power delivery. Higher CE source systems are preferred to realize the EUVL system. The general expression of CE is given by

\[
CE = \frac{E_{EUV_{2\%BW_{2\pi}}}}{E_{\text{input}}}
\]

where \( E_{EUV_{2\%BW_{2\pi}}} \) is the radiated energy in 2% bandwidth (BW) into \( 2\pi \) sr and \( E_{\text{input}} \) is the energy coupled into the source plasma. The two percent BW requirement is set by the reflectivity bandwidth of the series of multilayer mirrors used in the system, and is the bandwidth of radiation transferred to the photoresist on the wafer.

For any source configuration to satisfy the source output power requirement, the CE must be high enough to relax other parameters in the equation,

\[
P_{IF} = \eta_R \times \eta_{Col} \times CE \times P_{\text{input}}
\]

where \( P_{IF} \) is the power measured at IF, \( \eta_R \) is the average mirror reflectivity over the total collection angle, \( \eta_{Col} \) is the collection efficiency of the solid angle of the mirror over \( 2\pi \) and \( P_{\text{input}} \) is the input power. One can easily calculate the impact of the CE value on the input power needed. The reflectivity of collection optics is around 50% and the collection angle is approximately \( \pi \) steradians. To achieve 115 W at IF, the input power must be greater than 46 kW with CE of 1.0 %, 20 kW with CE of 2.3 %. The input power as well as the CE value can be relaxed by increasing the collection angle. Where the collection angle as large as \( 2\pi \), say with a CE of 2.3 %, which is achievable [14], then the input power could be as low as 10 kW.

1.1.4 Source lifetime

Similar to the conventional light sources used for today’s lithographic stepper machines, EUVL sources are required to operate for a specified lifetime. The minimum lifetime
requirement is currently set at 30,000 hours, where a total number of source plasma generations is on the order of $10^{11}$ for the minimum repetition rate of 7 kHz. This minimum repetition rate is set by the required dose stability, and is dependent on the source power stability, assumed here to be $< 1\%$. The collector mirror reflectivity is the only factor that changes over time and is allowed to have a reduction of up to 10 % over the mirror lifetime [15]. Reduction comes from the source plasmas emitting not only radiation but also ions and particles of the target material that will degrade the reflectivity over time. It is a challenge to achieve long term plasma source operation without having any mirror reflectivity degradation. The primary objective of the study reported in this thesis is to identify the causes of the mirror degradation and to characterize the particulate debris and high energy ion emissions. In addition, the prevention of the mirror degradation by mitigating the debris and the ion emission will also be investigated.

### 1.2 EUV - Soft X-ray sources

The term "EUV" is new, coming into use only during the last decade to describe the wavelength range of light in the $\sim 10$ nm range. This is traditional called the Soft X-Ray range ($\sim 1$ nm - 70 nm). However the lithography community preferred to use the term "EUV" to imply it being an extension of the current deep UV (DUV) methods (193 nm) currently now in place. From an over-view perspective, EUV and soft X-ray radiation can be generated either directly from transient motion of electrons or by the de-excitation of excited bound electron in partially stripped ions. To generate an electromagnetic (EM) wave with short wavelengths by the former mechanism, the acceleration of the electrons has to be large in order to create a fast electric field transient. The radiation of synchrotrons, undulators, and wigglers are based on the acceleration of the relativistic electrons. In the latter mechanism,
hot-dense plasmas are the sources of excited ions, existing in several ionization stages, that gives rise to EUV or Soft X-ray emission. Gas discharge dense plasmas and laser produced plasmas are generated easily in laboratories.

1.2.1 Synchrotron radiation

Deflection of an electron with a high magnetic field results in an acceleration of the electron directed to the center of the circular motion. Conservation of energy and momentum dictates that EM radiation is emitted in a cone tangential to the electron’s trajectory. The acceleration of electrons must be large in order to radiate high frequency EM waves in the EUV and soft X-ray regions. The most successful application of the radiation emission based on electron acceleration is synchrotron radiation. Figure 1.2 [16] illustrates how the radiation is generated when an electron experiences a strong acceleration as described. The half angle of the confined radiation is inversely proportional to $\gamma$ ($\gamma \equiv 1/(1 - v^2/c^2)^{1/2}$) and $\gamma \gg 1$ for highly relativistic electrons [1]. From the lithography point of view, synchrotron radiation is perfect for fundamental research. The radiation produced in this manner is clean, there is no particle emission, it is highly confined and spectrally welldefined. However, synchrotron facilities are large and expensive and the EUV flux is not high enough for use as a source for EUVL. Although they were initially considered for EUVL, research in the past decade has shown that hot plasmas sources are more advantageous in terms of the foot print, maintenance cost, and capability of integration with the lithographic stepper machines.
1.2.2 Gas discharge dense plasmas

There are two types of hot-dense plasma sources under development, laser plasma sources and gas discharge sources. To attain radiation from plasmas predominately emitted into the EUV regions, plasma temperatures of several tens of eV are required. The most common gas discharge plasmas are created so-called "pinch plasmas" between electrodes with unique geometries where the discharge current confines the plasma itself and the pinch confinement progressively increases the plasma temperature and density. The pinched plasma subsequently collapses due to the growth of magneto-hydrodynamic instabilities.

Several different discharge configurations have been devised. Hollow cathode triggered gas discharge [17], dense plasma focus plasmas [18], Z-pinch gas discharges [19], and capillary discharges [20] are some of the typical configurations. A schematic of a gas discharge plasma source configuration is shown in Figure 1.3 [21]. The debris generation process from gas
discharge plasmas is complex. The plasma as well as the electrodes can be the source of debris. The lifetime of the electrode must be factored into the source lifetime, and the electrode lifetime is one of the challenges gas discharge plasmas need to overcome.

Due to the electrode structures and confined radiation from pinched plasmas, gas discharge EUVL sources utilize grazing incidence mirrors to collect the radiation. This configuration is suitable for use with foil trap mitigation schemes, which is indicated as the "Debris Shield" in Figure 1.3. Applying the foil trap mitigation to laser plasmas is discussed in Chapter 7.

![Diagram of gas discharge plasma source configuration](image)

Figure 1.3: Schematic of gas discharge plasma source configuration [21].

### 1.2.3 Laser plasmas

Laser plasmas are hot dense plasmas induced by laser irradiation of a material surface. To produce such plasmas on a target surface, the laser beam is focused into a small area. The laser intensity measured in W/cm² is the most significant factor for determining the plasma temperature. The radiation is generated by electrons experiencing strong electric fields of
ions (free-free emission) and also by the electrons de-excited in the energy levels in the atoms and ions (bound-bound emission). There is no lifetime limitation on creating laser plasmas if the target material is delivered continuously. The source lifetime of the EUV light source is simply the lifetime of collector mirror reflectivity. A reduced mass target can be used to reduce the debris generation in the plasma. Details of the laser and target material configurations are discussed in Chapter 2. From the mitigation point of view, which differs from gas discharge plasma sources, any mitigation schemes around the plasma block the collected radiation. An example of a source, mirror and IF configuration for utilizing laser plasma is shown in Figure 1.4 [22]. A suitable mitigation configuration is discussed in Chapter 7.

![Figure 1.4: An example of laser plasma EUV source, mirror, and IF configuration [22].](image-url)
1.3 Multilayer mirror coating and reflectivity

The refractive indices of materials approach unity when the radiation wavelength approaches EUV and soft x-rays. Refractive optics and reflective optics are very difficult to be created for use with these wavelengths. Most materials absorb radiation at wavelengths in the EUV and soft x-ray regions. However, multilayer coatings enable reasonably high reflectivity at specific wavelengths by choosing the materials with small absorption at those wavelengths. The general absorption properties of materials and the basic ideas of multilayer mirrors are discussed in this section.

1.3.1 Absorption of soft X-ray in materials

The general form of the refractive index [1] as a function of the frequency of the radiation is expressed in,

\[ n(\omega) = 1 - \delta + i\beta \]  

(1.4)

where \( \omega \) is the frequency of radiation that propagates in the material. The absorption decay length (skin depth) is expressed by,

\[ l_{abs} = \frac{\lambda}{4\pi\beta} \]  

(1.5)

where \( l_{abs} \) is the distance until the electric field is reduced to 1/e. The expression shows that the decay length is proportional to the wavelength and the absorption is based on the complex component of refractive index. The complex component of the refractive index is expressed with the atomic scattering factor.

\[ \beta = \frac{n_a r_e \lambda^2}{2\pi} f_2^0(\omega) \]  

(1.6)

where \( n_a \) is atomic concentration of the material, \( r_e \) is the classical electron radius, and \( f_2^0 \) is the complex component of the atomic scattering factor. The atomic scattering factors of
most of the elements are found on the Center for X-Ray Optics (CXRO) website [23]. When
macroscopic characteristics of absorption are considered, absorption is expressed as,
\[
\frac{I}{I_0} = e^{-\rho \mu r} \tag{1.7}
\]
where \(I\) is the intensity of incident wave measured at a distance of \(r\) from the surface, \(I_0\) is the intensity of the wave at the surface, \(\rho\) is the density of the material, and \(\mu\) is the absorption coefficient. The absorption coefficient is also expressed by the atomic scattering factor,
\[
\mu = \frac{2r_e \lambda}{Am_u} f_2^0(\omega) \tag{1.8}
\]
where \(A\) is the atomic mass of the material, and \(m_u\) is the unit atomic mass. The absorption coefficient is proportional to the wavelength and the complex component of the atomic scattering factor. There are rapid changes in the atomic scattering factors both of the real and complex components as a function of wavelength [1, 23]. They are based on the resonance of the bound electrons which differ from element to element. Therefore, the absorptions of materials for short wavelength radiation are dependent on the nuclear structures in the material atoms. In Chapter 3, more detailed absorption characteristics of thin films or thin layers are described for materials that are important for the mirror reflectivity degradation.

1.3.2 Reflectivity of multi-layer mirror

The key to the high reflectivity of the multilayer mirror (MLM) is constructive wave interference [1]. Typical multilayer coatings have a periodic structure of materials consisting of a low Z material and a high Z material. The low Z materials are used just as spacers where low absorption is expected. The high Z materials are used as absorbers where higher absorption is expected. The high Z materials introduce a large difference in the refractive index in the coatings. A cross section of multilayer mirror is shown in Figure 1.5 [24]. As
radiation is propagating in the coating, the wave is scattered at each layer having the large refractive index. The wave propagation and scattering are constructively interfered when the wavelength in the coatings satisfy the Bragg’s law,

$$m\lambda = 2d \sin \theta$$  \hspace{1cm} (1.9)

where $m$ is an integer number, $d$ is the thickness of the each period of the multilayer coatings, and $\theta$ is the grazing angle of the wave.

Figure 1.5: TEM cross section image of Mo/Si multilayer mirror surface [24].

The reflective coating materials selected for EUVL are Si and Mo. Typical reflectivity characteristics of a multilayer coating with Si and Mo is shown in Figure 1.6 [25]. The peak reflectivity is about 0.7 and the bandwidth of the reflectivity is about 4\% of 13.5 nm. Only the radiation generated in the source plasma with the wavelength in the reflectivity band is reflected. The rest of the radiation with wavelength outside the reflectivity band will be absorbed by the mirror, resulting in mirror heating. The EUV mask is created on the multilayer mirror surface by depositing absorbing materials with the desired pattern [26]. There are at least 6 multilayer mirrors in the projection optics before the EUV radiation reaches
the photoresist [27]. Figure 1.6 also illustrates how the EUV radiation is attenuated through the series of mirrors and how the bandwidth is reduced to 2%. The EUVL photoresists are required to have a sensitivity of 5 mJ/cm². The radiation generated in the plasma source is delivered through the IF and is used to illuminate the EUV masks. The illumination must be sufficient to expose the photoresists at the required dose in order to have the final productivity of 100 wafers per hour [12]. The EUVL source collector mirrors consist of the multilayer mirrors with characteristics that are identical to what is shown in Figure 1.6.

![Si/Mo Multilayer mirror reflectivity](image)

Figure 1.6: Reflectivity characteristics of Si/Mo multilayer coatings [25].

### 1.4 Summary of background and motivation

It is necessary for the semiconductor industry to utilize shorter wavelength light sources in the lithographic machines in order to continue the advancement of microchips. The
most promising technique is EUVL, which utilizes a hot dense plasma source and multilayer mirrors. The plasmas are generated using either gas discharges or lasers. The requirements that need to be met by the light sources are challenging, especially in the areas of 1) EUV power delivery and 2) the lifetime of the source and the collection optics. The EUV power requirement is based on the photoresist sensitivity and the overall transmission of the series of multilayer mirrors. The lifetime of the EUVL light source is determined by the lifetime of the collector mirror reflectivity which is degraded by debris from the plasma.

The main mechanisms causing mirror reflectivity degradation are deposition and erosion, which are discussed in Chapter 3. A common approach to reducing debris generation and to extending mirror lifetime is to reduce the target mass. Even though the mass of the target is reduced, collector mirror reflectivity degradation still occurs. The target material can coat the mirror surface, leading to the absorption of EUV radiation. Energetic ions created in the plasma can cause multilayer mirror surface sputtering as well. It is important to characterize the mirror reflectivity degradation processes in order to identify the cause and to prevent degradation, thus extending mirror lifetime. In this study target material deposition processes, ion emission characteristics and debris mitigation are investigated. Finally, the potential of a laser plasma source to be realized as an EUVL source is discussed in this study.
CHAPTER 2
LASER PLASMAS AND DEBRIS

2.1 Introduction

In this chapter, a description overview of laser plasma generation, debris generation, and mass-limited target concepts including different target configurations are presented. The laser plasma generation process involves the absorption of laser pulse energy, transitions in the existing ionization stages, and thermal energy transfer to kinetic energy. During the production of plasma on a solid surface different kinds of debris are also generated, each posing a threat to the collection optics. The debris generation processes and different target configurations are discussed in this chapter. There are many existing target configurations that are designed to reduce debris generation. A common approach to minimize debris is to reduce the mass of target. The ultimate goal of the approach is to realize a target where the mass is limited to the minimum number of ions required for efficient radiation, which is called the mass-limited target concept [28]. During the plasma generation process, while utilizing a mass-limited target, the entire target is ionized. The knowledge of the number of atoms in the target enables quantitative debris emission characteristics, which are discussed in the later chapters. A short description of how to calculate the total number of atoms in the target is also presented in this chapter.
2.1.1 Laser Plasma generation

Temperatures in laser plasmas typically exceed hundred thousand degrees Kelvin which is equivalent to tens of eVs. (The plasma temperature is usually expressed in the unit of eV where 1 eV is equal to 11604 K.) Simultaneously, the densities of these plasmas are high since they are generated near the surfaces of solid. These plasmas have a large number of multiply ionized ions which are the source for short wavelength radiation. The electron transitions that have energy between the levels in such ions are typically tens of or hundreds of eVs. The photons generated by electron transitions in these energy levels have energies that correspond to the wavelengths in soft X-ray and EUV region. The laser pulse energy is absorbed efficiently by the plasma in the region of high electron densities. Due to the high electron density as a result the plasma expands rapidly and cools down. Most of the thermal energy is transferred to kinetic energy. The ionization stages of ions are lowered by recombination with electrons while the plasma is expanding.

2.1.2 Absorption of laser energy in fully ionized plasmas

The photon energy of a laser pulse is typically a few eV while the temperature of plasma can exceed 10s of eVs. Laser plasmas can be heated by many processes involving electrons, ions and photons. The leading absorption mechanism for an EUV source is called three-body absorption or inverse Bremsstrahlung absorption which relies on the electrons absorbing the laser light. The electron mass is much lighter than the ions in the plasmas so the electrons can oscillate with the electric field in the laser pulse. When an electron approaches an ion, the electron experiences a Coulomb force. This force causes strong electron acceleration due to the small mass of electron and the small distance between the electron and ions. The electron radiates photons like that of synchrotron radiation but at an atomic
scale, which is referred as Bremsstrahlung radiation. The inverse of this process, where a photon is absorbed by the collision process, is called inverse Bremsstrahlung absorption (IBA).

The IBA process is the main absorption mechanism of a plasma when the laser intensity is $10^{10}$ to $10^{12}$ W/cm$^2$, and the interaction of the laser light is with a plasma scalelength considerably longer than the light wavelength. The coefficient \([29]\) of IBA is expressed in

$$K = \frac{16 \pi Z^2 n_e n_i e^6 \ln(\Lambda(\nu))}{3c\nu^2 (2\pi m_e k_B T)^{3/2}} \frac{1}{(1 - \nu^2/\nu_p^2)^{1/2}}$$

(2.1)

where \(Z\) is the ionization state of ions, \(n_e\) is electron density, \(n_i\) is ion density, \(e\) is charge unit, \(c\) is speed of light, \(\nu\) is frequency of laser light, \(m_e\) is mass of electron, \(k\) is Boltzmann constant, \(T_e\) is electron temperature, \(\nu_p\) is plasma frequency, and \(\ln(\Lambda) = \ln(\nu_T/\omega_p p_{\text{min}})\) is called the Coulomb Logarithm \([30]\). The plasma frequency is expressed as

$$\nu_p = \frac{1}{2\pi} \omega_p = \frac{1}{2\pi} \sqrt{\frac{e^2 n_e}{\epsilon_0 m_e}}$$

(2.2)

where \(\epsilon\) is permittivity. \(p_{\text{min}}\) is the minimum impact parameter for electron and ion collisions which is the maximum of either \(Ze^2/kT\) or \(\hbar(m_e kT)^{1/2}\). The IBA coefficient is high when the electron density is high and electron temperature is low. This \(n_e, T_e\) dependencies show that the laser light is absorbed by the surface of the target at the beginning of plasma generation. As a result of laser absorption creating high electron temperatures, the plasma expands resulting in an electron density gradient on the front of the target. The newly formed low density part of the plasma becomes transparent to the laser light allowing the inner part of the plasma near the target to absorb the laser light. This laser light penetration occurs progressively until all the laser energy is absorbed by the plasma or the laser light encounters the plasma region whose frequency is equal to the laser light frequency. The \(1/(1 - \nu_p^2/\nu^2)^{1/2}\) term in Equation 2.1 causes the IBA coefficient to be infinite when the two
interacting frequencies are equal. In general, an EM wave is reflected by plasmas with a plasma frequency higher than that of the incoming EM wave. This frequency is referred as the electron plasma frequency, sometimes called the cut off frequency. For a specific laser wavelength to be the cut-off frequency of the plasma, the electron density is obtained by substituting the laser frequency in the plasma frequency in Equation 2.2. This electron density is referred to as the critical density and for 1064 nm laser light is about $10^{21}$ els. cm$^{-3}$.

In addition to the IBA process, resonant absorption can occur at the critical density. The process is resulting in strong local energy deposition and this causes hot (non-thermal, collisionless) electron generation. The hot electrons can escape from the plasma once they become out of phase with the resonant oscillation due to collisions with ions. The escaping hot electrons will then drag nearby ions by Coulomb attraction these ions acquiring high kinetic energies. This latter process is not likely to occur in the laser intensity region of this study.

### 2.1.3 Ionization stages

The degree of ionization in the plasmas in this study is relatively high. For example the tin ions will have about ten electrons stripped off at the plasma temperature of 30 eV [31]. A tin atom has 50 electrons and the ionization potentials of tin ions range from about 7 eV to 300 eV until it becomes Kr like (Sn$^{14+}$ ion). For lower Z materials, for instance, lithium ions will have all the electrons except one stripped when the plasma temperature reaches 10 eV [32]. The ionization stages are determined by the ionization potentials and the electron temperatures.

With a plasma generated by IBA on a slow enough time-scale, (for the absorbed
energy to equilibrate in the plasma) it can be considered to be a thermalized plasma. Then a maxwellian distribution can be used to describe the electron temperature. A higher temperature of the distribution is sufficient to ionize the ions that the electrons collide with. It is explained by Saha’s equation [33],

$$\frac{X^2}{1 - X} = \frac{1}{n h^3} (2\pi m_e k T)^{3/2} e^{-I/k T}$$  \hspace{1cm} (2.3)

where $X = n_e/n$, hence ionization ratio, $h$ is Planck’s constant, and $I$ is ionization potential. The assumption of the equation is that the plasma is in thermal equilibrium. In hot dense plasmas, it is a reasonable assumption that the plasmas are at local thermal equilibrium (LTE). Although the plasmas are temporally and spatially non-uniform, a local region of the plasma at any time instant is in equilibrium. Due to the high frequency of electron and ion collisions, there are sufficiently high energy transfer rates from electrons to ions and vice versa. Under these conditions the ionization rate can be equal to the recombination rate. Figure 2.1 shows the population of ions as a function of electron temperature. The transition of ionization starts below the ionization potential, 10 eV for Figure 2.1. For high density, the plasma is fully ionized when the electron temperature is much higher than the ionization potential.

Similarly it is possible to calculate ion population for higher ionization stages [34, 35, 36]. The coefficients for ionization, radiative-recombination, and three body recombination at the $Z^{th}$ ionization state are expressed respectively in

$$S = \frac{9 \times 10^{-6} \xi_z (T_e/\chi_z)^{1/2}}{\chi_z^{3/2} (4.88 + T_e/\chi_z)} e^{-\chi_z/T_e}$$  \hspace{1cm} (2.4)

$$\alpha_r = 5.2 \times 10^{-14} (\chi_z/T_e)^{1/2} Z [0.429 + 1/2 \log(\chi_z/T_e) + 0.469 (T_e/\chi_z)^{1/2}]$$  \hspace{1cm} (2.5)

$$\alpha_{3b} = 2.97 \times 10^{-27} \xi_z / T_e \chi_z^2 (4.88 + T_e/\chi_z)$$  \hspace{1cm} (2.6)
where \( z \) is the ionization stage, \( \xi_Z \) is the number of electron in the most outer orbit of the stage, and \( \chi_Z \) is the ionization potential. Radiative Recombination is a process where an electron is captured by an ion and recombines into an excited level. Then the electron makes a radiative transition to a lower level. The Three Body Recombination process is one in which an electron is captured by an ion and the excess energy of the electron is sufficient to excite another electron. The excited electron eventually decays down to a lower energy state of the ion with consequential emission of radiation. The electron density rate at the \( Z^{th} \) ionization state is given by the equation [36]

\[
\frac{dn_{z+1}}{dt} = n_e n_z S(z, T_e) - n_e n_{z+1} [S(z + 1, T_e) + \alpha_r(z + 1, T_e) + n_e \alpha_{3b}(z + 1, T_e)] \\
+ n_e n_{z+2} [\alpha_r(z + 2, T_e) + n_e \alpha_{3b}(z + 2, T_e)]
\]

(2.7)

When a stationary state is assumed, the ratio of two adjacent ionization stages in equilibrium

Figure 2.1: Ionization rate calculation at different electron densities.
is expressed in,

\[
\frac{n_{z+1}}{n_z} = \frac{S(z, T_e)}{\alpha_r(z + 1, T_e) + n_e \alpha_{3b}(z + 1, T_e)}
\]  

For high Z materials like tin, some of the ionization potentials are so close that several ionization stages exist at the same electron temperature [37]. Figure 2.2 illustrates ion population for different electron temperatures for the case of tin plasma with the electron density of \(10^{21} \text{ cm}^{-3}\). The ionization potentials used in the calculation for the different tin ions are found in the literatures [38, 39].

![Figure 2.2: Population of tin ion species as function of electron temperature.](image)

2.1.4 Fluid descriptions of laser plasmas

There are a number of ways to describe plasmas mathematically. For example, a fluid expression that describes the temperature, pressure, and motion of the fluid in terms of hydrodynamics or fluid-dynamics can be applied. If as assumed previously, the electron
energy distribution is Maxwellian, the electron temperature is expressed by only one value. Similarly, temperature values can be expressed for other species as well. A set of (mixture of) multiple fluids is typically used to describe fluid characteristics of plasma. Typically, electrons and ions are the two interacting fluid species described.

There are three sets of equations [1, 40, 41] for each fluid species that are used to calculate the motion of fluid at different times. The electron temperature and density are typically calculated progressively along with instantaneous laser pulse energy. In this study, two different simulation codes are utilized which are discussed in Chapter 6.

Conservation of particle number is expressed in,

\[ \frac{\partial n}{\partial t} = -\nabla \cdot (n\vec{v}) \]  

(2.9)

where \( n \) is the density of a species and \( v \) is the average velocity. Conservation of momentum is expressed in,

\[ nm \frac{\partial \vec{v}}{\partial t} = -\nabla P + nq(\vec{E} + \vec{v} \times \vec{B}) - \vec{F}_{fric} \]  

(2.10)

where \( m \) is the mass of the species, \( P \) is the pressure, \( q \) is the charge of the species, \( E \) is electric field, \( B \) is magnetic field and \( F_{fric} \) is the friction force caused by collisions with other species. Conservation of energy is expressed in,

\[ n \frac{\partial U}{\partial t} = -P\nabla \cdot \vec{v} + \frac{\partial U_{trans}}{\partial t} + \frac{\partial U_{dep}}{\partial t} \]  

(2.11)

where \( U \) is the thermal energy, \( U_{trans} \) is the transferred energy due to collisions with other species, and \( U_{dep} \) is the energy deposited in the plasma. For the laser plasma case, \( U_{dep} \) is absorbed laser energy. The friction force term in Equation 2.10 is expressed in

\[ \vec{F}_{fric} = \sum_j \alpha_{aj} (\vec{v}_a - \vec{v}_j) \]  

(2.12)
for multi species case. The coefficient is expressed in each species pair

\[ \alpha_{ab} = n_an_bm_{ab}\alpha'_{ab} \]  

(2.13)

where \( m_{ab} = m_am_b/(m_a + m_b) \) is reduced mass from each mass of species. The coefficient \( \alpha' \) of friction force is expressed in,

\[ \alpha'_{ab} = \frac{4\sqrt{2\pi}Z_aZ_be^{4\ln\Lambda}}{3\sqrt{m_{ab}(kT)^{3/2}}} \]  

(2.14)

which is the collision frequency of two species.

The energy transfer term of the Equation 2.11 is a result of collisions between two different species where a temperature is higher than the other.

\[ \frac{\partial U_{trans}}{\partial t} = \sum_j 3n_a\alpha'_{aj}k(T_j - T_a) \]  

(2.15)

Based on these equations, a laser plasma is described from the beginning of the laser pulse, to the end when the plasma reaches the collector mirror after expansion. A simplified simulation model that utilizes these equations is constructed and the details of the simulation are described in chapter 6.

### 2.1.5 Plasma expansion

Plasma generated by a nanosecond Gaussian laser pulse starts to expand rapidly well before the laser power reaches the peak. The pressure gradient will accelerate the motion of plasma as described in Equation 2.10. Such expanding plasma is rapidly cooled down. As seen in Equation 2.11, decompression due to velocity divergence reduces the temperature if there is no energy addition. There is no mechanism to increase the ionization stages while the temperature is decreasing. The ionization stages will be reduced through recombination processes.
2.1.6 Recombination

As described briefly in section 2.1.3, ions recombine with electrons. The dominant recombination process in an expanding plasma is three-body recombination. The rate of electron density change due to the three-body recombination [29] is expressed in

\[
\frac{dn_e}{dt} = 5.6 \times 10^{-27} (kT)^{-9/2} n_e^3
\]

(2.16)

where the unit of density is cm\(^{-3}\) and \(kT\) is in eV. It is seen from the equation that the recombination rate is high in the plasma region with high density and low temperature. The electron density and temperature decrease while the plasma is expanding. The ratio of decrements of the density and temperature can be complex in the different regions of the plasma. A more detailed discussion by using simulation code is described in Chapter 6.

From the EUVL source configuration point of view, the ionization stages of ion species are important. The sputtering rate of the surface material of mirrors and the damage level of their surface structure depend on the ionization stages of the ions that impinge upon them, as described in the next chapter. A better understanding of recombination processes during the plasma expansion is therefore useful not only for the surface damage but also for the mitigation schemes. The measured ion emission characteristics are in good agreement with the prediction of the fluid simulations and these are discussed in Chapter 6. The ionization stages of ion flux at collector mirror surface are determined by the recombination.

2.2 Debris generation

Debris generation in laser plasmas has been observed by nearly all the research conducted using solid metals as targets.\[42, 43\] The term debris is refers to the material biproduct of useful emission, and is generally viewed as an undesired product of laser plasmas.
There are research fields where debris generation is useful. Pulsed laser deposition (PLD) is one of the largest research areas that use debris. In the PLD process, a laser beam ablates the target material and the ablated material is deposited on a substrate. PLD is a fast process, and it is possible to deposit compositions of targets which are preserved in the laser ablation [44]. These are the advantages of PLD over other deposition processes. As is seen in PLD, the focused laser beam creates not only plasma but also molecules, clusters, and larger size liquid/solid pieces that are not decomposed by the laser beam. In research areas such as EUVL, these material emissions are identified as debris.

2.2.1 Solid target and debris

When the laser beam is focused on the cold surface of a solid target, the temperature of that area increases rapidly. This rapid temperature increase causes thermal expansion of the material. The expansion occurs locally in the focal region and the material outside the focus is still cold. When the propagation of the high pressure region is faster than the heat transfer, the cold material at the boundary suffers severe damage such as cracks. When the material surfaces are cracked to small pieces and their kinetic energies are high enough to eject out of the surface, they become hot rocks and emanate from the target surface. The material portions that are heated high enough to become liquid phase will break up into aerosols (smaller droplets). To distinguish these droplet from the droplet target, in this thesis ”Arosols” is used to express these small droplets. The liquid starts to expand and eject from the target surface due to the pressure gradient near the target surface. The aerosols also fly out into the environment.

Hot rocks and aerosols can be created without plasma generation. Ions, neutral atoms, radicals, and electrons are created during plasma generation when the laser irradiation is high
enough to produce plasma. The energy coupled into the plasma generation is transferred to the kinetic energies of ions, electrons, neutral atoms, radicals or molecules. As shown in Chapter 6, the ion emission can be lethal to the multilayer mirror surface.

Laser plasmas produced from a solid target will generate all varieties of material emission as mentioned above. This debris generation is one of the limitations in using laser plasmas for industrial applications. Due to debris issues, the preferred material in the early stage of EUVL source research was gaseous xenon. Xenon targets are believed to be debris free because it is inert gas and does not generate any hot rocks or aerosols.

### 2.2.2 Hot rocks and aerosols

Hot rocks and aerosols were observed early on in EUVL source development [45, 46]. Characterizations of debris, in terms of size, shape, velocity, and emission distributions were investigated and ideas for debris mitigation were discussed. The large sizes of particles are the most threatening factor causing damage to the x-ray optics near the source. The particles can be in solid and liquid phase. A perfect example describing the impact on the multilayer mirror surfaces introduced by hot rocks and aerosols are obtained from Li planar target and Sn planar targets [47]. Figure 2.3 shows optical microscope images, 3D profiler images, and the cross sections of the profiles of multilayer mirror surfaces for both Li and Sn targets. Microscope images show a number of material particulates on the mirror surfaces. The 3D profiler images show a more detailed view of the surface damage. The debris generated from the Li plasma shatters the multilayer mirror surface, a consequence of the flying by hot rocks. In contrast, the debris generated by Sn plasmas is seen to create deposits on the sample surface as a result of flying aerosols. Surface damage caused by hot rocks from Sn plasma is also observed. Both types of damage degrade the mirror reflectivity despite
the differences in the degradation process. The generation of hot rocks and aerosols can be eliminated by applying the mass-limited target concept which is described in a later section. The degradation processes are described in more detail in Chapter 3.

Figure 2.3: Comparison of multilayer mirror surfaces exposed by Li and Sn plasmas [47].

2.2.3 Ions, electrons, and neutral atoms

Because the plasmas are generated by the laser pulse, there are always ions and electrons present. Due to the small mass of electrons, the damage caused by electron flux is negligible. Depending on the mass of ion species, ion incidents can cause severe damage to the multilayer structure. The damage appears as erosion of the mirror surface over the number of plasma generations. There are neutral atoms depending on the ionization ratio of the plasma and on the recombination processes after the plasma generation. A neutral atom of the target material has the same mass as the ions of the material. Thus the damage caused by neutral atoms is similar to the damage caused by ions. The degradation process caused
by ions is discussed in Chapter 3 and the measurement of ion flux and energy distributions is discussed in Chapter 6.

2.3 Mass-limited target

Debris free laser plasma sources are realized by reducing the emission of the hot rocks and aerosols to a minimum. The first step to reduce the debris from the laser plasmas is to utilize reduced mass of the target. The EUVL source development trend is reducing the mass of the target and varying in different target materials, compounds, geometries, and the way to supply the targets to the laser focus. However, at the same time the radiation in the useful band is required to be high enough to be a useful light source. The only target configuration that provides both the minimum debris and the maximum radiation is the mass-limited target [28, 48]. The mass-limited target contains just sufficient number of radiator atoms and the entire target is ionized up to the desired plasma temperature for the required radiation. As the results of the complete ionization, there are no hot rocks or aerosols generated. The target configuration trend in the EUVL source developments is described.

2.3.1 Different target configurations

There are a number of compositions and geometries for target delivery in the EUVL source development field in order to realize the reduced mass targets. They can be categorized into three types; Xe targets, liquid metal targets, and tin doped targets. Xenon targets are one of the candidate materials for the EUVL source. Xenon is in gas phase at room temperature so that the target material does not deposit or block the EUV radiation on the multilayer surface. However, Xe in gas phase does not have high enough atomic concentra-
tion to be an intense laser plasma source. Therefore Xe is cryogenically cooled to the liquid phase, and is delivered to the laser focus region. There are three distinguishable configurations for Xe target delivery. The Xe cluster target configuration [49] is accomplished by supplying cryogenically cooled Xe into a cooled capillary nozzle. The Xe filament target [50] is accomplished in the same manner as the Xe cluster target but requires higher purity and precise temperature control. The Xe droplet target [51] is accomplished by applying periodic perturbation on the nozzle and the Xe filament will break up into periodic droplets under the medium vacuum environment. In both the latter approaches, the Xe filaments freeze due to evaporation in transit in the vacuum chamber, prior to breaking into droplets. Due to the low CE of Xe targets [37], all the knowledge of Xe target configurations is transferred to realize the liquid metal target configuration.

The typical liquid metal targets that have been reported are the Sn filament [52], the Sn droplet [53], and the Li droplet [53]. The metal is heated in a reservoir to become liquid and conveyed to a heated nozzle instead of cooling for Xe target cases. Sn is an efficient material and it has more ion species which emit EUV than Xe does [37, 54]. Recently researchers have investigated the EUVL source development using Sn for gas discharge plasma sources [55] as well. Li is also an efficient material that researchers have been investigating since the early EUVL source development [20, 56]. The liquid metal target configurations are reported as higher CE targets than Xe. However, the disadvantage of the liquid metal target configuration is the opacity of the plasma which is generated near the solid/liquid density of metal. The opacity is caused by self-absorption in dense plasma and the effects are seen by changing tin concentration in solid targets [37].

Tin-doped target configurations are investigated by several research groups. Tin-doped droplet targets [57] are applied to this study where the CE and radiation studies have
been conducted by previous and current colleagues [58, 59]. The tin-doped target is the only masslimited target configuration and realized by making droplets with SnCl₂ solution. Another target configuration in which tin is chemically doped is SnO₂ cell targets [60]. The tin particle can be doped into the target [57] and being developed by mixing tin particles into water and making droplets containing these tin particles [61]. These tin doped target configurations reduce not only the total mass of the target but also the mass of tin in the target. A small mass of tin reduces the debris generation which is important in utilizing this metal for EUVL sources. Similar reductions are expected by reducing the density of metal targets. The density can be reduced by ablating solid or liquid metal targets before the heating laser pulse is focused on the target. One common method to reduce the target density is to use pre-pulse [62]. However, the larger part of the target materials remains at the solid density and it is not producing any EUV radiation. This unused target material is wasted and moreover can generate the hot rocks and aerosols. Thus for all the target configurations, controlling the target mass is an important factor to reduce debris generation.

2.3.2 Number of atoms in a target

As described previously, the EUVL source development trend is utilizing the reduced mass of the target, where the number of atoms that produce the EUV radiation is unknown. In contrast, counting the number of atoms in the target is possible once the mass-limited target is realized because all of the materials are consumed in producing the plasma. With the knowledge of the number of atoms in the target, it is possible to analyze debris quantitatively and the analyses are described in Chapter 5 through 7. The number of atoms in a specific target can be calculated with some reasonable assumptions and approximations. For the droplet targets in this study, one important assumption is that the size of each individual
droplet is equal to all the droplets generated. This is a reasonable assumption when the droplets are created by a capillary nozzle with stable stimulation at a constant frequency [63] as the target material breaks into uniform size droplets that are equally spaced.

There are several ways to determine the size or mass of the target. Microscopy of the target using a short-pulse back-illumination at a given magnification and resolution determines the diameter of the target. To obtain the number of atoms in the target, it is necessary to know the density of the target material and the mass concentration of the target composition. Another way is to calculate the size of the droplet. The flow rate of the material is determined by measuring the outer diameter of the material jet, and velocity of the target. The volume of the target is calculated by the flow rate and the frequency of the stimulation. The velocity is obtained by measuring the spacing between adjacent droplets and the period of the stimulation. The density of the target has to be known as well. The easiest way to measure the mass flow rate is to capture the target materials ejected in a small container in a given time duration. This method provides the mass of the target directly by dividing the mass flow by the frequency. The density of the target does not have to be known to count the number of target atoms.

The number of atoms in the target for this study is calculated as follows. The captured mass of the target per minute is $1.0 \times 10^{-1}$ g and by dividing the total number of target generation of $6.0 \times 10^6$ (100 kHz), the mass of a single droplet is found to be $1.7 \times 10^{-8}$ g. The fractional mass of all the elements in the target solution are in the ratio $H:O:Cl:Sn=0.06:0.49:0.17:0.28$. The mass of tin in the target droplet is $4.8 \times 10^{-9}$ g where the mass of a single tin atom is $2.0 \times 10^{-25}$ kg. Therefore the number of tin atoms in the target droplet is $2.4 \times 10^{13}$. In addition, the number of tin atoms decreases or increases as the driving frequency changes. The number of tin atoms can therefore be scaled by the
driving frequency. The typical frequencies for this study are 30 kHz, 50 kHz and 100 kHz. Thus the numbers of tin atoms used are $4.8 \times 10^{13}$ and $7.2 \times 10^{13}$ for 50 kHz and 30 kHz respectively.

### 2.4 Summary of laser plasmas and debris generation

Typical mechanism of laser plasmas which are generated with laser intensities of $10^{10}$ to $10^{12}$ are IBA, characteristics of high ionization stages, rapid plasma expansion, and three body recombination. A fluid description of plasma can be used to express how the plasma expands and how the plasma parameters change at different times. The generation of debris from laser plasmas on solid targets is lethal to the collector mirror surfaces. Different types of target configurations that utilize reduced mass of the target are being investigated for EUVL source development. However, only the mass-limited enables comparison between the number of atoms in the target and debris emission and flux at the collector mirror surfaces.
CHAPTER 3
MULTILAYER MIRROR REFLECTIVITY
DEGRADATION

3.1 Introduction

As described in Chapter 1, the lifetime of the EUV light source is evaluated at the intermediate focus (IF). To deliver the required EUV power to the IF, the collection optics is considered a part of the EUV light source. For droplet plasma source the reflectivity of the collector mirror is based on normal incident multilayer mirror structures. Any absorbing materials on the top of the multilayer coatings caused by deposition and oxidation will reduce the reflectivity and thus the source lifetime. Any structural degradation of the multilayer coatings caused by surface sputtering, observed as erosion, can also reduce the reflectivity, and hence the lifetime. This chapter discusses the reflectivity degradation processes and impacts of deposition, oxidation and erosion on the multilayer coatings.

3.2 Deposition

As described in Chapter 1, the periodic structure of Si/Mo layers is the key to achieving high reflectivity at 13.5 nm. In this chapter the processes that will degrade the mirror reflectivity are considered. Once the periodic structure is destroyed the mirror reflectivity drops precipitously. Any absorbing materials on the mirror surface will degrade the reflectivity as well, even if the mirror structure maintains high reflectivity characteristics. As discussed in Chapter 2, the debris generated from laser plasmas can destroy the multi-
layer coatings. These debris emissions from the plasmas are the most threatening factor for
the multilayer coatings. Also discussed is how the laser plasma based on the mass-limited
target concept can eliminate incident of particulates of target materials. However, since
the plasmas are generated in vacuum, the target material emanates as the plasmas expand.
Depending on the ion kinetic energies, typically smaller than 100 eV [64, 65], the metallic
ions are deposited on the multilayer mirror surfaces. The target materials that deposited
cause mirror reflectivity degradation. In this section, the absorption of a thin film of target
material is discussed.

3.2.1 EUV absorption of target materials

Most materials used as laser plasma target materials absorb EUV radiation due to
the fact that since the radiation is generated by electron transitions in the ions, it can be
absorbed by other electron transitions in other ions and atoms. Figure 3.1 illustrates the
absorption coefficients for possible target materials, Li, Sn, and Xe. The characteristics are
calculated by using Equation 1.8 and the \(f_2^0\) values are referenced from the Center for X-Ray
Optics (CXRO) website [23]. All the target materials have absorbing properties for EUV
radiation with photon energies of approximately 90 eV. The unit of the absorption coefficient
is \(\text{cm}^2/\text{g}\). Li is a much lighter element than Sn so for a given volume or given thickness of
these two materials, Li has less absorbing properties as can be seen from Equation 1.7. Xe
is in a gas phase at room temperature so that EUV radiation absorbed by Xe gas is smaller
than that by Li and Sn. However, a much larger effort is required to pump Xe gas out of
the source chamber since it is much heavier than air. If cooled liquid Xe is continuously
supplied in the chamber without having high enough vacuum pumping power, the number
of Xe atoms in the source chamber will increases. The density of Xe gas is lower than that
in the solid or liquid phase. However, the absorption is not negligible because the radiation experiences a longer path in the Xe filled environment. For any of these target material it is important to remove the target atoms in the optical path of the EUV radiation.

![Absorption coefficient](image)

Figure 3.1: Absorption coefficient of Li, Sn, and Xe.

### 3.2.2 Absorption estimates of thin film

When target materials are deposited on the multilayer mirror surface, the mirror reflectivity drops due to absorption in the film. The reduction factor depends on the thickness of the deposition and its coverage area on the surface. Usually the multilayer structures are preserved under the deposition unless the deposition layer diffuses into or reacts chemically with the multilayer structures. As described in the previous section, the EUV radiation absorbed by the target atoms can be estimated from known atomic scattering factors, and the density of the materials. Figure 3.2 compares the transmission of thin films made of Si, Nb,
Ru, Li, and Sn. The transmission characteristics of Si, Nb, and Ru are shown as references since they are commonly used as capping layers for multilayer mirror coatings [66]. The materials for the capping layer are chosen for their low absorption of EUV radiation and their high chemical stability in preventing oxidation and carbonization. Thus the transmissions of those materials are required to be high. The transmission curves are obtained by the calculation program available on the CXRO website [25]. The transmission of Sn thin film is significantly lower compared to other materials.

Figure 3.2: Transmission of thin film 10 nm of Si, Nb, Ru, Li, and Sn [25].

The EUVL stepper roadmap requirements stipulate that the transmission of the deposition layer can cause no more than a 10% reduction in the reflectivity at the end of the mirror lifetime. This sets the maximum thickness of the depositing layer. The latter must be reduced to half this value because the double path of the radiation on the mirror surface must be considered. As can be seen, the maximum thickness of deposited thin layer of Li
can be up to 5 nm. The transmission of a Sn thin film with 1.5 nm thickness is close to 90%. Thus the maximum thickness for Sn deposition is only 0.75 nm to provide a < 10% reduction factor.

### 3.2.3 Oxidation of multi-layer mirror surfaces

Oxidation of the multi-layer mirror surface has a similar effect on the reflectivity degradation to the degradation as that caused by deposition. Oxygen is a strong absorber of EUV which makes oxides so detrimental. Usually oxidation occurs at the interface of the multilayer coatings to the vacuum environment, however, the oxidation process is rather complex. In addition, once the silicon surface is oxidized, it is very difficult to remove the oxidized layer. To prevent the oxidation of Si a so-called "Capping layer" is deposited on the Si surface. More research on oxidation has been reported in the area of the projection optics than on the collection optics as the impact of oxidation of the mirror to the projection optics is more significant than that to the collection optics. Researchers are currently investigating the oxidation processes [67], reducing the oxidation rate [68], and removing the oxidation from the capping layers [69]. In this section the impacts of absorption from the oxide layers on the collector mirror optics are discussed.

### 3.2.4 Absorption of an oxide layers

A similar calculation of the EUV absorption characteristics of thin films described in the previous section is carried out for the case of oxide layers. Figure 3.3 shows an example of the transmission of SiO and SiO$_2$ layers as compared to a Si layer with the same thickness. The EUV absorption caused by oxygen atoms is dominant for oxide layers due to the high transmission of Si. A thickness of 10 nm is just sufficient to keep the reflectivity within the lifetime requirement of 10% reflectivity degradation. This is equivalent to oxidation of only
a half of the top Si layer of the multilayer structure, assuming uniform oxidation. Because of
the process, a SiO$_2$ layer thickness of approximately 5 nm results when a Si layer thickness
of about 2.4 nm is oxidized. If the entire Si top layer is oxidized, the reflectivity drops more
than the requirement. Therefore oxidation has to be minimized as much as possible.

![Graph showing transmission of oxide layers](image)

Figure 3.3: Transmission of oxide layers [25].

### 3.2.5 Photon induced oxidation processes

The oxidation process of the multilayer coating is a complex process. Several re-
searchers have reported that the process involves EUV radiation. The first result, which
is reported from the engineering test stand [70] (ETS), indicates that the oxidation rate is
significantly higher under EUV radiation exposure [69]. Another study has reported that
the oxidation process is a function of EUV dose, EUV intensity, and residual pressures of
oxygen or water vapor [67]. The EUV dose is measured in J/mm$^2$, and the EUV irradiance
is measured in W/mm$^2$. Some research reports that just the residual water pressure is not the key for oxidation of a Ru capping layer [71]. The presence of hydrocarbons influences the oxidation processes as well. Other researchers report on reducing the oxidation rate with hydrocarbons [72], on modeling the oxidation processes [73] and removing oxidation layer from Ru capping layer with use of hydrogen [70].

### 3.2.6 Impact on oxidation on collector mirror surfaces

The impact of oxidation on the collection optics is discussed in the previous section. Although the relationship between water pressure and the oxidation rate is not simple, the tendency for oxidation can be used to estimate the reflectivity lifetime of the mirror. Figure 3.4 shows the mirror reflectivity degradation as a function of EUV dose, and the degradation slope as a function of EUV intensity [67]. The reflectivity drop is measured under water pressure of 1 x 10$^{-4}$ Pa. The degradation slope is linear with respect to the EUV intensity. The experimental condition is approximately 10 mW/mm$^2$, which is typical for the projection optics. The EUV irradiance at the collection optics is around 1 mW/mm$^2$ which is one order of magnitude lower than that in the projection optics. The irradiance is based on uniform illumination of the mirror, the mirror distance from the plasma source of 20 cm, and the source power of 300 W in 2% $2\pi$ sr. By extrapolating the slope characteristics in Figure 3.4, the slope of 1 x10$^{-5}$ mm$^2$/J can be obtained at the EUV irradiance of 1 mW/mm$^2$. For 10% reflectivity reduction, a dose of 10$^4$ J/mm$^2$ is required. At the irradiance of 1mW/mm$^2$, the lifetime is about 10$^7$ s, which is equivalent to 3,000 hours. It is one order of magnitude shorter than the lifetime requirement. This indicates the possible threat to oxidation of the collection optics.
The experimental conditions that are used in estimating the mirror lifetime are slightly different from the conditions where the collection optics are located. The collection optics are exposed to not only EUV radiation, but also to radiation at other wavelengths and especially to ions generated in the plasmas. In the projection optics, there are no ions sputtering the multilayer mirror surface which is the main reason for the significant impact of oxidation on the mirror surface. Due to the ions generated in the source plasma, the oxidized top surface of the collector mirror is simultaneously sputtered off. When the plasma source is integrated with debris mitigations, which are discussed in Chapter 7, ultimately the only mirror degradation process is oxidation. Advances in research for the capping layers in projection optics can be applied, and more detailed research on oxidation of the collection optics will be necessary in the future.
3.3 Erosion on multi-layer surfaces

The erosion of the multilayer mirror collection optics is caused by high kinetic energy ions sputtering off the surface atoms as described in Chapter 2. Besides oxidation of the multilayer mirror found in ETS, erosion is also observed at the collection optics surfaces [74] The ETS collector mirror reflectivity degradation indicated that some 15 bi-layers were removed over $5 \times 10^8$ plasma generations for the EUV source conditions used. This source utilized the Xe cluster target. A follow-up experiment on ETS suggested high energy ions with kinetic energies up to 60 keV [75]. However, the evidence for these high energy ions was not completely confirmed, and if evident, may well have been a consequence of using the Xe cluster target.

Another multilayer mirror erosion study was carried out using water droplet target [76]. The target geometry and the laser intensities for the water droplet target were equivalent to the conditions applied to this study. The mirror erosion was found to be caused by the high energy oxygen ions, which is shown in Figure 3.5. The erosion is an accumulated result of extensive sputtering caused by high energy ions generated by each plasma event. Therefore, understanding the sputtering characteristics of materials used in the multilayer coatings, as well as the ion kinetic energy distributions, are very important for the erosion studies.
Figure 3.5: SEM image of a multilayer mirror surface showing the evidence of the erosion caused by high energy oxygen ions [76].

3.3.1 Surface sputtering process

When an ion is incident on a solid surface, some atoms of the solid eject out of the surface. This sputtering process can be described as a result of cascaded collisions in the surface atoms. Depending on the kinetic energy of the incident ion, the sputtering yield, whose unit is the number of the target atoms ejected per incident ion, change. A number of experimental results and models are reviewed and summarized in the literature [64]. Not only a wide range of ion energies, but also ion species and solid materials have been investigated. The sputtering yields are characterized as functions of the energy and mass of the incident ion, atomic number of target materials, incident angle, and target temperature. In this study the sputtering yields of Si and Mo are essential, particularly, as a function of incident energy of Sn$^+$. However, there is no experimental data for the sputtering yields. Thus, a computer simulation is performed in order to obtain the sputtering yields.
3.3.2 A Monte Carlo Simulation - SRIM

Monte Carlo simulations (Monte Carlo method) are widely used for many applications. The Stopping and Range of Ions in Matters (SRIM), is a Monte Carlo simulation code that models the collisions in target materials caused by high energy incident ions \cite{77}. One of the results of the simulations is the sputtering yield averaged over specific numbers of incident ions. It can simulate the sputtering of nearly all the elements for many incident ion species and all the elements and desired compounds as targets \cite{78}. The calculated results have been favoritely compared with experimental results \cite{79, 80}. The calculation and utilization of the results are described in Chapter 6.

3.3.3 Multilayer mirror reflectivity characteristics

As sputtering progresses the total thickness of the periodic structure of the multilayer coatings decreases. The consequences of the reduced thickness of the coating, reduced number of multilayers, results in reduced reflectivity. To illustrate the contribution of the number of bilayers to the multilayer mirror reflectivity, the reflectivity characteristics are obtained from the CXRO website \cite{25}. Figure 3.6 shows a lower reflectivity peak but wider reflectivity band for a smaller number of bi-layers. Based on these characteristics, about 15 bi-layers are allowed to be removed from 40 bi-layer stack to hold high reflectivity to be within the 10% reflectivity drop limit for mirror lifetime.
It is possible to extend the mirror lifetime with sacrificial layers on the Si top layer similar to the capping layers as described before. Theoretically the peak reflectivity can be improved slightly with increased number of bi-layers [25]. Drawbacks of the sacrificial layers are the increased manufacturing costs of the mirrors and the possible defects due to the increased number of layers, such as the surface roughness and the interfacial roughness between the layers [81].

3.4 Summary of multilayer mirror reflectivity degradation

It is important to isolate the processes that produce multilayer mirror reflectivity degradation. Processes like deposition and oxidation do not create any structural degrada-
tion. Only a few sub-nanometers of material deposition or only the oxidation of the top layer is sufficient to attenuate EUV radiation to below the required level. Erosion is a long-term degradation mechanism and is a result of the mirror surface sputtering caused by high energy ions generated in the plasmas. Monte Carlo simulations are widely used to predict sputtering rates. This simulation approach can be used with known ion emission characteristics in terms of ion flux and kinetic energies to calculate the lifetime of collection optics. To maintain the required source lifetime requirement, the number of layer pairs in the multilayer mirror can be reduced from, say 40 to 25, for an ideal case without impairment of the reflectivity.
CHAPTER 4
EXPERIMENTAL FACILITIES

4.1 Introduction

For studies of debris generation, detection and mitigation, higher repetition rate plasma sources are needed to simulate the operation conditions. The laser system used for this study is a 100 Hz Nd:YAG laser system. Debris and debris mitigation studies are performed separately from radiation and metrology studies in a dedicated vacuum chamber. The tin-doped droplet target is injected into the target chamber and the laser pulse generation is synchronized so that every laser pulse is focused onto a single droplet target. Debris is detected in two ways, deposition diagnostics and ion diagnostics. Debris detection in combination with several mitigation schemes are also carried out. Two different mitigation schemes are applied; electrostatic field mitigation, commonly referred to as the Repeller Field, and a combination of foil trap and magnetic field mitigation, called Magnetic Foil Trap mitigation.

4.2 Experimental facility

4.2.1 High repetition rate (100Hz) Nd:YAG laser system

A commercial laser system (Spectra Physics Quanta-ray GCR-190) is used for this debris study. It is a Q-switched Nd:YAG laser with a maximum laser pulse energy $\sim 300$ mJ, the
pulse duration is $\sim 10$ ns, and the repetition rate is 100 Hz. The laser beam is focused onto the target using a lens with focal length of either 50 mm or 100 mm. By considering the reflectivity of the mirrors and the transmission of the optical components from the laser output to the target, the maximum energy on the target is about 150 mJ. The minimum focus diameter is calculated to be $80 \mu m$ and the maximum intensity at the target is about $3 \times 10^{11}$ W/cm$^2$. The laser system is shown in Figure 4.1. The average laser output power is monitored during experiments by a power meter.

![Figure 4.1: Photo of the laser system](image.png)

4.2.2 The target chamber

The vacuum chamber used for this debris study is cylindrical with an inner diameter of about 20 cm and is equipped with a turbomolecular pump. The low pressure in the target chamber is kept typically at around $4 \times 10^{-4}$ Torr during the experiments. The optical setup of the chamber is shown in Figure 4.3. The axis of vacuum chamber is indicated by the
alignment HeNe laser beam. The heating laser pulse enters one side of the target chamber and exit from the other side coaxial with the alignment beam axis. The heating laser is focused at the position of target delivery. An additional lens collects transmitted laser beam light and the nearly collimated beam is stopped by beam block installed outside chamber. The heating beam line outside chamber is enclosed for eye safety by three cages which are made of acrylic sheet. The droplet targets are supplied from top via a three axis adjustable feed though. One of the large (8”)ports of the vacuum chamber has a glass window and is used as an observation port. The other side of the 8” port is used for various diagnostics and is divided into different angles. One of the custom vacuum flanges has two ports at about 80 degrees and the other at 97 degrees. Another vacuum flange has one port at 90 degrees. They are exchangeable for different experimental purposes. There is another port used for diagnostics at 90 degrees from the laser axis and 45 degrees from the horizontal plane. A photo of the target chamber is shown in Figure 4.2

![Figure 4.2: Photo of target chamber](image)

50
4.2.3 Target delivery

The target containing 30% tin in a water solution is delivered from a capillary nozzle. The number of tin atoms doped in a target is near $10^{13}$ atoms. The 30 - 100 kHz train of uniform droplets (from 30 $\mu$m to 50 $\mu$m in diameter) is generated with a piezo-driven nozzle assembly and the droplets have a velocity about 20 m/s. The nozzle assembly is mounted on a 3D translation stage with flexible vacuum bellows so that the position of the droplet is adjusted from outside chamber. The droplet conditions and stability are monitored by an imaging system with a CCD camera having an optical resolution of approximately 2 $\mu$m. The illumination of the imaging is made by a laser diode and is delivered from outside chamber as shown in Figure 4.3. The laser diode is modulated at the same frequency as that is supplied.

Figure 4.3: Schematic of optical setting on the target chamber
to piezo-crystal but the pulse duration is less than 1\(\mu\)s. With the pulsed laser illumination, the droplet targets appear as dark circles on the imaging system. The frequency of piezo signal can be changed in order to have stable target delivery. Unused targets are captured by a cryogenic cold trap in order to prevent evaporation in the vacuum chamber. Figure 4.4 shows orientations of the target delivery, cold trap, heating laser pulse and imaging system.

### 4.2.4 Target laser synchronization

The synchronization of the laser pulse and the droplet target is accomplished by electrical signal synchronization of droplet signals and laser flash lamp trigger signals in combination with a delay generator and mechanical translation. The laser operates at around 100 Hz while the droplet targets are generated at a frequency of 30 kHz to 100 kHz. The droplet and laser frequencies are synchronized by a phase lock loop (PLL) circuitry. The synchronization is performed at a higher frequency \(\sim 4\) MHz and the signals are divided by counters to provide stable signals. The signal with the lower frequency passes through an adjustable delay circuit then goes to the flash lamp trigger on the laser system. It is reasonable to assume that there is constant delay from the flash lamp trigger signal to actual laser pulse generation in the laser system. It is also a reasonable assumption that the droplets travel at constant velocity due to no air drag in the vacuum environment. As described in Chapter 2, the droplet generation is periodic and that the sizes and velocities are uniform. Based on these assumptions, only adjustment of the delay is required to synchronize the laser pulse and target. The timing diagram of the synchronization is shown in Figure 4.5. A custom synchronization system has been designed and built to have all the functionalities of PLL, divider, and delay circuit. The synchronization system is operated by a PC by communicating over the parallel port.
Figure 4.4: Orientations of target delivery, cold trap, heating laser pulse, imaging system, and a visible image of the plasma observed by the imaging system.
4.3 Debris diagnostics

The primary purpose of this study is to detect debris. The detection can be accomplished by observing evidence of debris emission and deposition/erosion and a common method is to use a witness plate capture. The samples are characterized separately after the capture, post shot, utilizing different types of characterization facilities. It is an ext-situ detection. It is also possible to detect debris in-situ utilizing acoustic wave sensors. Any shifting in surface acoustic oscillation or bulk acoustic oscillation caused by mass transfer can be detected. Analysis on the frequency shifting requires knowledge of different characteristics of deposited materials. Detecting plasma expansion is also an in-situ characterization. There are different kinds of charged particle detection in plasmas. A Faraday cup ion probe and ion spectrometers are used in this study.
4.3.1 Witness plate capture and post shot analysis

Glass plates, silicon wafers, and multilayer mirrors are used as witness plates in order to capture debris particularly deposits. The witness plates are installed in the target chamber and exposed to the plasma source for a specific time duration where the number of plasma creations is known. The witness plates are removed from the chamber after the exposure and then analyzed by using different types of surface characterization methods. The characterization facilities that are used in this study are Optical Microscopy (OM), Atomic Force Microscopy (AFM), Scanning Electron Microscopy (SEM), Auger Electron Spectroscopy (AES), X-ray Photon Spectroscopy (XPS), Rutherford Backscattering Spectroscopy (RBS), and an optical 3D profiler.

A variety of witness plate installations are possible and are applied throughout this study, an example of which is shown in Figure 4.6. A custom built witness plate holder with kinetic motion feed-through is mounted on a vacuum flange. The plate can be installed and uninstalled during an experiment without having to bring the entire chamber to atmosphere. A photo of the sample holder is shown in Figure 4.6. Typically the witness plate samples are placed at distances which are equivalent to the distance of the collector mirror, about 10 to 20 cm. If it is assumed that the tin atom emissions from a single target are uniformly distributed into the entire solid angle, the tin deposition rate is in the order of $10^{-12}$ g/cm$^2$ per laser shot. Here the total mass of tin inside a target as described in Chapter 2 is used. By using the density of solid tin of 7.3 g/cm$^3$, the number of laser shots required to have tin deposition of 0.75 nm is more than $10^6$ shots. This thickness is the maximum tin deposition permissible on the collector mirror surface. It is challenging to demonstrate uniform deposition at the distances using the witness plate capturing method with the 100 Hz laser, which can take at least 3 hours without any sputtering considerations. During the
long term exposure of the witness plate, the laser-target interaction condition can change causing tin aerosol generations and depositions, which are described in Chapter 5. However, it is a very useful method to observe the aerosol generation and the deposition which are discussed in Chapter 5.

Figure 4.6: Experimental setup for (top) witness plate and (bottom) sample holder
4.3.2 Deposition monitor

A quartz crystal microbalance (QCM) is a widely used to detect material deposition on crystal surfaces especially in plasma process facilities such as chemical vapor deposition (CVD) systems. The acoustic oscillation frequency is a function of deposition mass on the crystal surface as well as the crystal temperature. It is usually used in combination with another crystal that is shielded from the deposition, to compensate for any temperature shift. Typical sensitivities of QCM’s [82] are $\sim 10^{-9} \text{g/cm}^2\text{Hz}$ depending on the fundamental frequencies. The frequency of oscillation is in MHz range. It is challenging to detect the deposition level at the collector mirror equivalent distances. A more sensitive device than the QCM is a surface acoustic wave (SAW) oscillator [83, 84]. However, this is even more sensitive to the ambient temperature [85]. These monitors can be better used for high repetition rate plasma sources, which are discussed in Chapter 8.

4.3.3 Faraday cup ion probes

Ion probes are widely used, not only in EUVL source research, but also in other plasma related areas of research [75, 86, 87, 88, 89, 90]. The ion probes used in this study are custom designed to measure the low flux of ions expected from the low mass plasma targets. A schematic is shown in Figure 4.7. The ion probe collects all the charged particles unless an electrostatic potential is applied to the grid located in front of the cup electrode. To measure positively charged ions, a negative potential of approximately -60 V is typically applied. The ion probes detect the burst of X-ray radiation from the source, generating photoelectrons on the cup electrode. This photoelectron signal determines the plasma event time used for time-of-flight (TOF) ion measurements. From the TOF, and the distance between the ion probe and the source, and the velocity of the ions can be determined assuming they have
constant velocity. If the ion species that are producing the signal are known, then the ion kinetic energies can be calculated from the known mass of the ions.

![Diagram of Faraday cup ion probe]

Figure 4.7: Schematic of Faraday cup ion probe

### 4.3.4 Ion spectrometer with electrostatic ion energy analyzer

While the IP collects a variety of ions, an electrostatic ion energy analyzer (ESIEA) ion spectrometer detects selected ions with a corresponding kinetic energy. Figure 4.8 shows the schematic of the ion spectrometer. The spectrometer consists of an ion flux limiting aperture, a field-free path for TOF analysis, an energy analyzer, and an ion detector. The diameter of the aperture is 1 mm which selects a known fraction of the ion flux, and is placed at the distance of 10 cm from the source, equivalent to the distance of the first collector mirror in an EUVL source system. Behind the aperture, a separate vacuum chamber is attached to the target chamber as a field-free drift region for separating each ion species as they move at
different velocities. The vacuum of the entire ion spectrometer assembly is kept at less than $1.0 \times 10^{-6}$ Torr. The geometry of the ESIEA consists of a set of two electrodes with the shape of a circular quadrant. Two 1 mm slits are placed at the entrance and the exit of the analyzer. By changing the applied potentials of the electrodes, one can selectively analyze the ions with the kinetic energies (KE) having different charge states (Z) and mass (M). The ion detector placed right after the analyzer detects those filtered ions with the same KE/Z and different TOF. A single channel electron multiplier (CEM) is used for detecting the filtered ions. The distance from the plasma to the CEM is 900 mm. Thus a complete ion spectrum can be obtained by a series of ion measurements with the ESIEA set for different values of KE/Z.

![Schematic of (ESIEA) ion spectrometer](image)

Figure 4.8: Schematic of (ESIEA) ion spectrometer
4.3.5 Thomson parabola spectrometer

The Thomson parabola spectrometer (TPS) can resolve all ion species at one time. It is advantageous for low repetition plasmas typically produced from solid planar targets. In this spectrometer, the ions stream through small apertures and deflected by parallel electric and magnetic fields. The trajectory of each ion species traces out its own unique parabolic shape orthogonal to the incident axis. The motion of an ion is governed by the equation,

\[ m_a \frac{\partial^2 \vec{r}}{\partial t^2} = q(\vec{E} + \frac{\partial \vec{r}}{\partial t} \times \vec{B}) \]  

(4.1)

where \( r \) is the position of the ion in meters, \( m_a \) is the mass of the ion in kg, \( q \) is the charge of the ion in Coulombs, \( E \) is the electric field in V/m, and \( B \) is the magnetic field in Teslas. The motion is determined by the mass-charge ratio \( m/q \) and the velocity. A multi-channel plate array (MCP) coupled to a phosphor screen can then provide energy distributions for each value of \( m/q \). Figure 4.9 (a) shows the schematic of TPS and (b) shows a TPS signal. A trace of an ion species are expressed in,

\[ r_x = \frac{\partial \vec{r}_x}{\partial t}|_{z=z_e} \frac{l}{\frac{\partial z}{\partial t}} + r_x|_{z=z_e} \]  

(4.2)

\[ r_y = \frac{\partial \vec{r}_y}{\partial t}|_{z=z_e} \frac{l}{\frac{\partial z}{\partial t}} + r_y|_{z=z_e} \]  

(4.3)

where the coordinates \( x, y \) are on the MCP plane, \( z \) is along with the TPS axis, \( z_e \) is the position at the exit of the analyzer, and \( l \) is the distance between \( z_e \) and the MCP plane. The bright spot of the MCP image corresponds to the axis of the TPS system. The spot is lit by the radiation from plasma. Thus an ion species is identified with trace coordinates with regard to the bright spot and a calculated trace using the Equations 4.1 through 4.3.
4.3.6 Amplified ion probe

For ion flux measurements with two mitigation schemes, which are discussed in Chapter 7, ion flux becomes so low that IP cannot detect ions efficiently. The amplified ion probe is constructed in order to detect low ion flux. Similar to the ESIEA spectrometer, a single channel electron multiplier (CEM) is used as an ion detector. A negative high voltage (-3 kV) is applied to the CEM. The amplified signal is monitored by an oscilloscope. An aperture whose diameter is 2 mm separates the ion probe section from the target chamber in order to have high vacuum by a turbo pump. The CEM distance from the plasma source is 250 mm. The schematic of the amplified ion probe is shown in Figure 4.10.
4.4 Mitigation schemes

Preventing mirror reflectivity degradation by applying different mitigation schemes is the second objective of this study and two types of mitigation schemes are applied. Electrostatic field mitigation (Repeller Field) applies a static potential between the plasma source and witness plates or ion diagnostics. Similarly Magnetic Foil Trap mitigation (MFT) is placed between the plasma source and the debris diagnostics. Based on the different mitigation concepts for the two mitigation schemes, the Repeller Field mitigation is installed close to the diagnostics while the Magnetic Foil Trap mitigation is installed close to the plasma source.
4.4.1 Electrostatic field mitigation

The Repeller Field mitigation concept is to repel charged particles before they reach the collector mirror surface. All charged particles experience the electric field. The particles are repelled when the forces generated by the electric field and the charge of the particles are large enough. Figure 4.11 shows the concept. The evaluation of the effectiveness of the field is carried out by using witness plates or ion diagnostics.

![Diagram of Repeller Field mitigation](image)

Figure 4.11: Concept of repeller field mitigation

Figure 4.12 shows an example of how the Repeller Field mitigation is installed with IP ESIEA, and witness plate diagnostics. A mesh electrode is used to apply the field potential, which is up to $\sim 600$ V without having discharge between the electrode and the chamber. The distance between the electrode and the grounded collimator is 5 mm and the length of the collimator is 25 mm. The electric field at the center of the collimator entrance is calculated to be $\sim 1 \times 10^5$ V/m. The IP and witness plates are installed right after the
collimator and the distance from the plasma to the IP is 64 mm. The ion limiting aperture 
of the ESIEA is installed at the opening of the collimator and the distance from the plasma 
to the aperture is 100 mm.

Figure 4.12: IP, ESIEA measurements with the repeller field, and witness plate measurement 
with the repeller field.

4.4.2 Magnetic foil trap mitigation

It is well known that charged particles are trapped by a magnetic field with cyclotron 
motions. In order to have a sufficiently small radius for tin ions relative to the source-collector 
mirror distance, for example the Sn$^+$ ion with 1keV kinetic energy, a uniform magnetic field 
of at least 1 T is required to trap the ion between the plasma and the mirror surface if the 
mirror distance of 10 cm is assumed. The foil trap mitigation scheme is also widely used 
especially for gas discharge EUVL sources and employs a number of thin plates, called foils, 
nested and placed in such a way that only radiation traverses the structure. This is typically
used with buffer gas or gas flow which makes particles straggle, bounce back and forth with the collision between the particles and the buffer gas atoms. The straggled particles are trapped by the foils. Because the configuration of the laser plasma EUVL sources where the radiation from the plasma is collected by a normal incident mirror and is reflected back to the IF, see Figure 1.4, it is impractical to enclose the plasma source with a foil trap and gas.

The Magnetic Foil Trap mitigation utilizes both magnetic field and foil traps. The magnetic field is used to deflect charged particles instead of a gas flow. Thus in this configuration the field is transparent to the radiation. In addition it utilizes only two permanent magnets with surface magnetic field of $\sim 1$ T, where the field strength around the plasma is reduced to $\sim 100$ mT due to the low permeability of the vacuum. The details of the mitigation scheme are discussed in Chapter 7. In order to investigate the effectiveness of the mitigation scheme, a single channel Magnetic Foil Trap is used, which is shown in Figure 4.13. Ion diagnostics, typically IPs are used to evaluate the effectiveness. Due to the limited diagnostic ports and physical space, the magnetic field is applied orthogonal to the heating laser axis. The magnetic field axis and foil trap channel are also orthogonal but 45 degrees from the horizontal plane. The magnetic field is provided by a set of permanent magnets and linked together with an iron core, which are shown in Figure 4.14. The foil angle, which is the angle the two plates make, can be adjusted for different experimental conditions. The distance from the plasma to the inner side of foils is typically 30 mm, and the outer side distance is about 100 mm. Figure 4.14 shows its photo.
Figure 4.13: Schematic of magnetic foil trap single channel experiment

Figure 4.14: Photos of magnetic foil trap single channel experiment setup (left) the magnetic core, (right) single channel foil.
4.5 Summary of experimental facilities

The experimental facilities including the laser system, the target chamber, the target delivery, and the synchronization are described. The debris detection techniques as well as the ion characterization techniques are discussed. The two debris mitigation schemes applied to this study are also described. By utilizing the witness plate post shot analysis, particulate debris emission characteristics and their impacts on the collector mirrors are discussed in Chapter 5. The ion emission from the tin-doped droplet plasma is characterized extensively using the ESIEA ion spectrometer in Chapter 6. The estimation of the mirror lifetime based on the characterized ion energy distributions as well as the detailed plasma expansions are also discussed in Chapter 6. The effectiveness of the mitigation schemes are evaluated in Chapter 7 in terms of reducing particulate debris and ion flux at the collector mirror distance from the plasma.
CHAPTER 5
PARTICULATE DEBRIS - AEROSOLS

5.1 Introduction

In this chapter the formation and characterization of particulate debris from the tin-doped droplet target are discussed. This target, specifically designed to minimize this debris, is reduced and the volume is comparable to, or even smaller than, the focus diameter of the laser pulse. The particulate debris depositions are observed on the witness plates. These deposits are identified as tin and their thicknesses are characterized. Due to the high absorption in tin for EUV radiation, as a deposit in the collection mirrors, the aerosols are lethal to the collector mirrors. The aerosol generation processes are investigated. It is found that the aerosol generation is minimized by optimizing laser pulse energy coupling to the target.

5.2 Aerosol deposition on witness plates

The idea of using mass-limited targets is to eliminate debris generation. However, the initial witness plate sample shows that there is still some particulate matter deposited on the surface as the plasma is produced from the tin-doped droplet. The deposits appear as thin splashes, supporting the notion that they are deposited at high velocities. It is reasonable to expect that these deposits are tin aerosols since there is no other metal element present in the target. Investigation of how the aerosols are generated, identification of the elements on
the witness plates, angular distribution of the deposition, and determination of the volumes of the deposits are performed.

5.2.1 Identification of the deposits

To identify the aerosols generated in the laser plasma, witness-plate post-shot analysis techniques are employed. These methods are commonly used to investigate debris emission from plasmas. The witness plates are placed in the source chamber during the source operation and these plates are investigated after the source operation. The identification of the surface materials require advanced spectrometry. Auger electron spectroscopy (AES) and X-ray photo-electron spectroscopy (XPS) are utilized in this study.

The initial experiment is carried out with a witness plate that is installed at a distance about 75 mm from the plasma source. The witness plate for this measurement is a piece of multilayer mirror. The number of plasma events generated is \(2.7 \times 10^5\). The plate is removed from the target chamber and is installed in an AES (Perkin-elmer PHI 600) and a XPS (Perkinelmer PHI 5600). The results of AES are shown in Figure 5.1 (a) and XPS in Figure 5.1 (b). Both spectra show evidence of Sn deposition as well as O and Si and a very small signal from Cl is seen in both measurements. Both of the spectroscopic techniques used are very sensitive to the surface compositions. Since there are no signals detected from Mo, the multilayer mirror witness plate is not ablated. Instead, the surface is covered by tin and possibly oxidized as well.
However, the sampling area of both these spectroscopic methods is rather large compared to the size of the deposited aerosols. Further analysis on the witness plate surface is performed by using AES with "point survey", which provides better spectral details from
a small surface area. "Point survey" or "point Auger analysis" is performed by aiming the incident electron beam to a point of interest and recording the Auger electron spectrum.

Two spectra are taken by the AES point survey. One is from the deposited aerosol and the other one is from the surface without any deposits for comparison. Figure 5.2 shows the comparison of AES spectra from the two points. By comparing Sn signals in the two spectra, the signal of Sn from the deposition is much larger than that from the surface. Thus the Sn signals in the AES and XPS are from those deposited tin aerosols.

![AES Sn signal comparison on the deposited aerosol.](image)

**5.2.2 Profile measurement of the deposits**

The same witness plate sample with deposits described above is used to determine the volume of the aerosols. An AFM (TA instrument µTA-2990) is used to determine the size of each aerosol. Typical AFM images are shown in Figure 5.3. An area of a 32.5 µm square was sampled with a resolution of 81 nm. Some of the larger deposits appear in the
form of rings. By analyzing the cross section profile of a deposit, the volume of the deposit can be calculated. The volume of the largest deposit is found to be $7 \times 10^{-13}$ cm$^3$ which likely consists of only tin and its mass is about $5 \times 10^{-12}$ g. The total mass on tin in the target is $4.8 \times 10^{-9}$ g. There are thousands of these aerosols generated during the laser target interaction. All the deposits are characterized in terms of their volumes since there is a clear trend of the volume as a function of the diameter of deposits. The trend is shown in Figure 5.4 and the approximation leads to aerosol flux estimation.

![AFM image of tin deposition on a multilayer mirror.](image)

Figure 5.3: AFM image of tin deposition on a multilayer mirror.

### 5.2.3 Aerosol flux calculation

Based on the diameter-volume relationship described above and the density of tin, the aerosol emission is characterized in terms of the total mass of tin. The mass of tin deposited in the AES sample area is estimated by categorizing the diameters of deposits and by counting the number of deposits. Figure 5.5 shows (a) the scanned AES image and (b) back-scattered AES image. The sample area is $140 \mu m \times 140 \mu m$. The image shown
(a) is similar to the SEM image and (b) indicates spatial distribution of high Z materials on the surface. The spatial distribution of the deposits shown in (a) and (b) are identical. Since there is no Mo signal detected in AES or XPS, all of the deposits in (a) are counted in the total mass estimation. The isotropy of aerosol emission is confirmed separately by the measurement of the angular distribution of deposits [91]. The solid angle of the AES sample area is calculated with the distance of the plate from the source plasma. The aerosol emission is estimated to be approximately 40% of total tin mass in the target. During the laser-target interaction, about one half of the tin contained in the target forms thousands of small aerosols. After the plasma generation the aerosols are deposited on the collection optics. Therefore the generation has to be minimized and aerosols have to be mitigated.

![Graph](image)

Figure 5.4: Deposit volume dependency of the diameters.
5.3 Aerosol generation processes

The number of aerosols generated from the tin-doped droplet laser plasmas is as seen in the previous section. However, the generation processes of aerosols in tin-doped droplet plasmas were not fully understood. The target droplet is in a solution form and the size of the target is smaller than the laser focus. Thus, all the material is being heated by the laser. The following three analyses suggest that aerosols are generated when the entire target is incompletely heated by the laser pulse. The laser intensities used in these three studies are set lower than the optimum.

5.3.1 Aerosol generation in low intensity laser irradiation

Two different doped targets are used in the low intensity laser irradiation experiment. Tin and copper are doped in water as chloride solutions, and the droplet targets produced...
with these (a) (b) solutions are irradiated using a low energy pulse. The energy of the laser pulse is less than 100 $\mu$J which is not enough to produce plasma. The transmitted laser pulse is detected by a photodiode so that the target and the laser pulse are synchronized. Glass witness plates are placed at a close distance from the laser focus, 15 mm, in order to capture low velocity aerosols which are expected to be generated with a low intensity laser focus. Both witness plates are exposed to over $6 \times 10^4$ laser shots. Optical microscopy shows aerosols deposited on the witness plate surface in both doped target cases.

These experiments indicate that the aerosols are generated with low laser energy, hence, low laser intensity. However, the temperature of these aerosols is hot enough to form liquid copper. The melting temperature of copper is 1085 degrees Celsius. There are many possibilities for the low laser intensity conditions even if the laser pulse energy is the optimum. If the droplet target is placed off the laser focus, the target experiences low energy laser irradiation. In fact, the first experiment is performed with a low level synchronization scheme. In addition, the target droplet generation has velocity fluctuations so that the operator had to control the target position all the time. Not only the target to be shot but also adjacent droplets can experience low energy irradiation. The laser light scattered off the source plasma can irradiate the two adjacent droplets. The radiation of the source plasma can irradiate the adjacent droplets, as well. In all cases, a low energy laser pulse will generate aerosols.

5.3.2 Origin of aerosol generation

Aerosol generation can be the result of incomplete heating of the target including secondary heating of the adjacent targets by the plasma radiation or scattered laser light. In order to determine the origin of the particle generation, the following procedure is applied.
First, a mask with a certain aperture profile is installed between the target and the witness plate. Second, the target separation is enlarged to eliminate the possibility of having the adjacent target heated directly or secondarily by the laser. Third, the target formation and positioning are carefully controlled during the exposure. No unwanted targets are close to the laser focal region. Lastly, the laser energy is reduced intentionally so that incomplete heating occurs. The plasma is generated by a 30 mJ laser pulse.

The mask and witness plate configuration are shown in Figure 5.6 (a) and the witness plate surface image is shown in Figure 5.6 (b). The distance between the transition from the deposited area to no deposition area is 75.7 $\mu$m vertically and 32.4 $\mu$m horizontally. With the geometry shown in Figure 5.6 (a), the size of the origin of the particles is 46.9 $\mu$m vertically and 20 $\mu$m horizontally which is equivalent to the size of the target. Thus, the particles are generated at the target and not at the adjacent targets.

![Figure 5.6: (a) distances of target, mask, and witness plate, (b) dark field image of the witness plate surface.](image)
5.3.3 Laser energy, intensity, focus diameter

Two more witness plate samples are produced using different plasma conditions. One plasma condition is created using a 30 mJ laser pulse, which is the same condition used for the particle origin determination experiment. The other condition is created by using a 120 mJ laser pulse which produces the condition for the optimum CE. The exposure is $1.2 \times 10^5$ shots for both cases. The witness plates are placed at 81 mm from the plasma, which is the same as described in Figure 5.6. The SEM images of those two samples are shown in Figure 5.7. As shown in Figure 5.7 (a), a number of aerosols are deposited on the surface, whereas only a few deposits are observed in Figure 5.7 (b). This comparison shows the target material irradiated by low energy laser pulse generates much more aerosols than the target irradiated by high energy laser pulse.

Figure 5.7: (a) SEM image of witness plate surface exposed by plasma created by 30 mJ laser pulse, (b) by 120 mJ pulse.
There is a relationship between irradiation conditions of high CE and minimum number of aerosol generation. When the target is irradiated by sufficient laser energy, the entire target is heated well enough to become plasma which emits EUV radiation. The laser intensity is calculated to be $1.2 \times 10^{11} \text{W/cm}^2$ with the laser energy of 120 mJ and the focus diameter of 100 $\mu$m. This intensity is equivalent to the intensity for the optimum CE [14]. The target diameter is calculated to be 42 $\mu$m with the droplet frequency at 30 kHz where the laser focus is more than the twice the target diameter. It is known that the droplet target starts expanding before the laser pulse reaches its peak [58]. With a typical plasma expansion velocity of $10^5$ m/s, the plasma expands from 40 $\mu$m diameter to 100 $\mu$m diameter in 0.3 ns. Even if a lower velocity is assumed for lower pulse energy before the peak, the time required for the expansion is approximately 1 ns. Therefore, a larger focus diameter than the target diameter is required to heat the entire target sufficiently.

5.3.4 Total tin atom emission

At the conditions isolated for obtaining high CE, only a very small number of aerosols are generated. It is reasonable to expect that the entire target is completely ionized. The plasma expands only as ions, electrons, and neutral atoms, if recombination of singly ionized ion takes place. Rutherford Backscattering Spectroscopy (RBS) is performed on the witness plate sample that was exposed to the plasma at high CE conditions as described previously. The tin atom concentration on the plate surface obtained from RBS analysis [92] is $2 \times 10^{15}$ atoms/cm$^2$. The total number of tin atoms is calculated to be $1.6 \times 10^{18}$ atoms over $1.2 \times 10^5$ laser pulses by assuming isotropic expansion of plasma. The total number of tin atoms is equivalent to about 18 % of the total mass of tin supplied into the droplet targets. The number is reasonable since some deviation from isotropic expansion is possible, and tin
self sputtering where the tin deposition layer is sputtered by tin ions, is also possible. The ultimate concept of the mass-limited target is finally realized by optimizing the irradiation conditions.

5.4 Summary of particulate debris

These experiments on aerosol generation in metal-doped droplet laser plasmas characterize this phenomena when the tin-doped droplet target is heated by laser pulses of different intensities. When the target is not sufficiently heated by the laser pulse, tin aerosols are generated. The sizes of aerosols range up to a few hundred of nanometers in diameter. Although the sizes of aerosols are small, the thickness of deposition is enough to attenuate EUV radiation below the required level. The aerosol generation can be minimized by optimizing the laser intensity and focus diameter. When it is optimized, the target is fully ionized. This fully ionized plasma source is then the source of energetic ions which can cause mirror erosion. The ion emission characteristics are discussed in the next chapter in great detail. It is also important to keep the target delivery stability in order to have optimized laser coupling to the target for long term operation, which is discussed in Chapter 8.
CHAPTER 6
ION EMISSION

6.1 Introduction

Once the whole target is ionized, the only threat to the collection optics reflectivity degradation is ions. High energy ions cause collector mirror surface sputtering. This chapter describes ion emission characteristics, especially, ion kinetic energy distributions at the collector mirror surfaces. By using the distributions and surface sputtering simulations, erosion rates are estimated. The erosion rates determine the lifetime of the multilayer mirror reflectivity. The most contributing factor on surface sputtering is high energy ions. The kinetics of plasma expansion is described by fluid-dynamics plasma simulations. Recombination processes that determine the ionization stages of ions at the collector mirror distance are discussed.

6.2 Ion emission characteristics

Ion emission produced by the plasma source can be measured by detecting charges carried by the expanding plasma. A Faraday Cup Ion Probe (IP) is commonly used to measure the ion flux. The ion flux measurement with an IP is simple but does not provide much information on individual ion species or the ionization stages. For example, tin-doped plasmas contain different mass of ion species ranging from hydrogen, 1 A.M.U. to tin 118.7 A.M.U. The ionization stages can be up to 11 for tin ions at the plasma temperature of 30 eV. To measure more detailed ion emission, ion spectrometry is necessary. An ion Spectrometer
configured as an Electrostatic Ion Energy Analyzer (ESIEA) is utilized. Quantitative analysis is made on the ESIEA to obtain ion energy distributions for each ion species. The laser intensity dependencies of the energy distributions are also characterized.

### 6.2.1 Ion flux measurement

Ion signals measured by the ion probe are shown in Figure 6.1. Using the TOF corresponding to the location at the peak signal, the ion velocity can be estimated. By using the peaks of the ion signals, the ion velocity estimations for three types of plasma sources are: $1.2 \times 10^5$ m/s for water droplet target, $1.1 \times 10^5$ m/s for tin 20% doped target and $1.0 \times 10^5$ m/s for tin 30% doped target. It is observed that ion velocities are lower for higher concentration tin-doped targets.

![Figure 6.1: Ion probe signals measured at 150mm from the plasma.](image)

A separate ion measurement was performed in the case of the solid tin planar target. The ion velocity from a 100 % tin concentration target is compared to the velocities of ions from water droplet targets and tin-doped droplet targets. Figure 6.2 shows the ion signals
from the solid tin planar target. The velocity of the peak is calculated to be $5.8 \times 10^4$ m/s which is less than half of the velocity from water droplet targets. This series of ion signals indicate that doping of tin causes ion signals to slow down. The slower expansion is easily expected because the mass of a tin atom is significantly larger than the mass of hydrogen and oxygen ions for the same kinetic energy.

![Graph showing ion probe signal from solid tin planar target](image)

**Figure 6.2:** Ion probe signal from solid tin planar target.

### 6.2.2 Mass spectrometer

Typical ion spectra are shown in Figure 6.3. The signal from the water target is shown for (a) KE=250 eV, and the signal from tin 30% doped target is shown for (b) KE=313 eV. In both signals, the ion probe signals are also shown as references when converted to the same distance of the CEM in the ion spectrometer.

Signals from different ion species are observed from both types of target. One peak in ESIEA signal is observed before the peak of the IP signal and is evident for both targets. Also, at least four lines around the peak and the decaying region in the IP signal are observed.
The first ESIEA signal is most likely from hydrogen and the latter signals are from oxygen (in Figure 6.3 (a)). As expected, four more signals are detected after the later part of the decay of the IP signal from a tin doped target. More detailed identification, analysis, and energy distributions are described in the following sections.

Figure 6.3: (a) Ion spectrum and ion probe signal from water droplet target, (b) Ion spectrum and ion probe signal from Tin 30% doped droplet target.
6.2.3 Quantitative ion spectrometer analysis

It is possible to obtain the entire ion spectrum for each ion species by applying a quantitative analysis on the ESIEA measurements. Each ESIEA signal is based on the number of ions in a small energy window which are based on the mass-charge ratio. By scanning the energy window throughout the ion energy range, the ion kinetic energy distributions for all the ion species are obtained. A series of measurements are necessary and the plasma conditions for all the measurements must remain same. The following section describes the quantitative analysis on ESIEA measurements applied to this study.

A typical ESIEA spectrometer signal is shown in Figure 6.4 (a). Several peaks are observed in the signal because the different components of the target material arrive at the detector at different times depending on their mass-charge ratio (M/Z). These signal peaks are generated by ions passing through the analyzer, and hold the relationship expressed by the following equation.

\[ Z e E = \frac{M_i v_i^2}{R_A} \]  

where \( Z \) is ionization state of the ion species, \( e \) is the unit charge, \( E \) is the transverse electric field inside the analyzer in V/m, \( m_i \) is ion mass in kg, \( v_i \) is ion velocity in m/s, and \( R_A \) is the radius of the analyzer path in meters. The ion velocity is determined by the distance of CEM from the source and the TOF. Then Equation 6.1 can be reorganized in terms of M/Z.

\[ \frac{M_i}{Z} = \frac{e R_A E}{m_p l^2} (TOF)^2 \]  

where \( M_i \) is the atomic weight of the ion of interest, \( m_p \) is the proton mass in kg, \( l \) is the ion CEM distance from the plasma in meters, and TOF is the time-of-flight in the signal in seconds. To identify all the signal peaks, the signal is converted to M/Z based signal by using Equation 6.2. A typical M/Z signal is shown in Figure 6.4 (b). The M/Z axis is
plotted in logarithmic scale. All the peaks in the signal are identified as specific ion species.

By keeping the same plasma conditions, it is possible to obtain M/Z signals with different energies by changing the electric field strength in the analyzer. It is then possible to plot all signals together and investigate the signal profile for a constant M/Z, shown in Figure 6.5 (a). However, because different M/Z spectra are converted from different TOF signals, the M/Z values in all the signals plotted do not lineup. A simple linear interpolation must be applied to all the converted signals. This complete map of M/Z spectra at a constant plasma condition is shown in Figure 6.5 (b). It is possible to make a profile for a constant M/Z, in other words, slicing the spectral map for each ion species can provide the ion energy distribution.

To obtain the ion energy distributions for individual ion species, it is necessary to count the total charge from the CEM signal peak and to calculate the number of ions analyzed in the energy window of the analyzer. By obtaining the efficiencies of the ion limiting aperture and the slit of the analyzer entrance, the distribution is calculated in terms of the number of ions per unit energy. Then the distribution is estimated in terms of the unit solid angle where isotropic ion emission is assumed. The details of the procedure are described in the following section and the schematics are shown in Figure 6.6.
Figure 6.4: (a) Typical ESIEA signal, (b) converted M/Z signal.
Figure 6.5: (a) Collected M/Z signals, (b) interpolated M/Z spectral map.
To count the number of electrons in each CEM signal peak, it is necessary to specify the analyzer energy window and the corresponding TOF window. First the nominal ion kinetic energy of the analyzer is expressed as

$$KE = \frac{1}{2} R_A ZeE$$  \hspace{1cm} (6.3)

obtained from Equation 6.1 by expressing $\frac{1}{2}m_i v_i^2 = KE$ where $KE$ is expressed in J. Because of the finite width of the slits of the analyzer, the analyzer has an energy window expressed by the equations.

$$\Delta KE = KE_{max} - KE_{min}$$  \hspace{1cm} (6.4)

$$KE_{max} = \frac{1}{2} \left( R_A + \frac{1}{2} \Delta R_A \right) ZeE$$  \hspace{1cm} (6.5)

$$KE_{min} = \frac{1}{2} \left( R_A - \frac{1}{2} \Delta R_A \right) ZeE$$  \hspace{1cm} (6.6)
where $\Delta R_A$ is the width of the slit in meters. The corresponding TOF window is expressed in the following.

$$\Delta TOF = TOF_{\text{min}} - TOF_{\text{max}}$$  \hspace{1cm} (6.7)

$$TOF_{\text{max}} = \frac{1}{l} \sqrt{\frac{M_im_p}{2 \cdot KE_{\text{max}}}}$$  \hspace{1cm} (6.8)

$$TOF_{\text{min}} = \frac{1}{l} \sqrt{\frac{M_im_p}{2 \cdot KE_{\text{min}}}}$$  \hspace{1cm} (6.9)

The signal integration can be calculated by multiplying the signal peak value and $\Delta TOF$ because the time constant of the CEM [93] is approximately 4 ns, much smaller than the acquisition time step of the signal. The number of electrons contributing to the signal peak can now be calculated using

$$-\frac{1}{e} \frac{V_p}{R_t} \Delta TOF$$  \hspace{1cm} (6.10)

where $V_p$ is the signal peak in volt, and $R_t$ is the terminal resistance of the oscilloscope in $\Omega$. Because the detected electrons are multiplied by CEM based on the incident ions, the number of the incident ions, $\Delta N_i$, is expressed in

$$\Delta N_i = -\frac{1}{\eta} \frac{1}{G} \frac{1}{e} \frac{V_p}{R_t} \Delta TOF$$  \hspace{1cm} (6.11)

where $\eta$ is the efficiency of CEM, and $G$ is the gain of CEM. Here $\Delta N_i$ represents the number of ions analyzed in the energy window $\Delta KE$. The ratio $\Delta N_i/\Delta KE$ is approximated to the notation of the energy distribution $dN/dE$ when $\Delta N_i$ is approximately constant or $\Delta KE$ is small. Finally, the ion energy distribution in terms of the number of ions per unit solid angle is obtained by calculating the efficiencies of the slit at the analyzer entrance and the aperture at known distances.

The following are the values in this study, $R_A$ is 25 mm, $\Delta R_A$ is 1mm which determines $\Delta KE$ to be 4.0% of nominal $KE$. $R_t$ is 50 $\Omega$ and $G$ is $10^6$ which is a typical value [93]. $\eta$
is 0.8 which is reasonable assumption for tin in the range of over 1 keV [80]. The collection ratio of the analyzer entrance slit is $9.8 \times 10^{-2}$ without considering ion beam divergence in the field free path. The efficiency of the ion flux limiting aperture is $6.3 \times 10^{-6}$.

With the calculation described, the ion energy distributions for individual ion species are obtained. The distributions of different tin ion species at laser intensity of $9.7 \times 10^{10}$ W/cm$^2$ are shown in Figure 6.7. Most of the ion emission detected is from low ionization states, typically less than Sn$^{5+}$. These lower ionization states that are observed at this distance from the plasma is compared to the ionization states contributing to the EUV radiation observed in the dense plasma source (Sn$^{9+}$ - Sn$^{11+}$). All the ion distributions are shown in appendix. The ion distributions are used in estimating the mirror reflectivity lifetime in a later section.

![Figure 6.7: Tin ions energy distributions at intensity of $9.7 \times 10^{10}$ W/cm$^2$.](image-url)
6.2.4 Emission dependency on the laser intensities

Ion emission characteristics are measured at different laser intensities. The ion probe measurements indicate that the increased plasma expansion velocities occur at higher laser intensities. Figure 6.8 shows the comparison between ion signals at different laser intensities. The plasma expansion velocities are measured to be $8.9 \times 10^4$, $1.0 \times 10^5$, and $1.4 \times 10^5$ m/s at intensities of $9.7 \times 10^{10}$, $1.9 \times 10^{11}$, and $2.8 \times 10^{11}$ W/cm$^2$ respectively. The plasma expansion velocity increases about 50% when the laser intensity is increased by three times.

![Figure 6.8: Ion probe signals at different laser intensities at 125 mm distance from the plasma.](image)

Ion energy distributions at different laser intensities are characterized. Higher kinetic energies and higher populations in higher ionization states are observed in higher laser intensities. The kinetic energy shift to higher energy can be explained by the higher plasma temperature due to the higher laser intensities. Higher ionization states can be the result of lower recombination rates at the high temperature, as seen in Equation 2.16. Ion kinetic energy distributions of oxygen ions and tin ions at three different laser intensities are
shown in Figure 6.9 and Figure 6.10 to illustrate these trends in different ion species. For all species including the distributions which are not shown, general trends mentioned above are observed. Another trend that is observed is a large slope in the high energy region of each ion energy distribution, especially for the singly and doubly ionized species. The population differences are large in the low energy side of the slope and high energy side of the slope. The difference ranges from one order of magnitude to three orders of magnitude within the ion populations. However, as illustrated in the case of ion energy distribution of Sn$^{5+}$, peaks in population are observed at the high energy side. These peaks are seen to shift to higher energy when the laser intensity is increased. The peaks correspond to the kinetic energy with the plasma expansion velocities measured by ion probes and also they are calculated in fluid simulations which are discussed later in this chapter.
Figure 6.9: Ion kinetic energy distributions of (a) O+, (b) O$^{2+}$, (c), and O$^{5+}$.
Figure 6.10: Ion kinetic energy distributions of (a) Sn+, (b) Sn$^{2+}$, (c), and Sn$^{5+}$.
6.3 Erosion study

Understanding the details of the ion flux and kinetic energies, as well as the resulting damage on the collector mirror surfaces is important in obtaining a complete picture of the effect of ion emission on the collector mirror. However, erosion is a very slow degradation process. The evaluation of surface sputtering requires long term exposures. It is therefore challenging to detect erosion at the mirror distance especially for low ion emission from tin-doped target plasmas. The current experimental setup for long term exposure is also limited by the laser repetition rate (100 Hz) of the laser used. Therefore, Monte Carlo simulations are adopted to study erosion on the multilayer mirrors. The sputtering rates of Mo and Si are calculated with measured ion kinetic energy distributions. From this analysis the estimated mirror lifetime is about two orders of magnitude lower than the lithography roadmap requirement. Although this appears a formidable difference, this level of mirror degradation is many orders of magnitude less than all other plasma sources currently under development. To satisfy the roadmap requirement, mitigation is necessary and this is discussed in the next chapter.

6.3.1 Limitation of laser repetition rate

The precise estimation of mirror lifetime is carried out using the measured ion energy distributions at the mirror distance and the surface sputtering simulations, instead of compromising expensive collector mirror over the large number of plasma generation cycles. The main reason for this estimation approach is because the plasma generation cycles in the facility used in this study is limited by the later repetition rate, which is only 100 Hz and the required number of plasma events is in the order of $10^{11}$. Generating this many events using a 100 Hz laser will take about 300 years! Even if a high repetition laser is used to generate
the plasma at the specified repetition rate in the EUVL source requirements, it will take a few years to reach the required number of plasma generation cycles. Therefore, estimating the mirror lifetime using the kinetic energy distributions and the surface sputtering yields is a reasonable method for any EUVL light sources development. This is the first time this approach has been adopted to estimating the lifetime of the collection mirrors. As described in Chapter 3, no experimental reference is available for Si and Mo surface sputtering on tin ion bombardments in different kinetic energies. Thus the widely used SRIM simulation code [78] is used to calculate the sputtering yields of Si and Mo on the tin ion bombardment.

6.3.2 Lifetime estimation of mirror reflectivity degradation

Figure 6.11 shows the SRIM calculations of the incident ion energy dependences of sputtering yields for Si and Mo surfaces. The sputtering yields in the range of 400 eV to 10 keV are approximated using the least square methods. The integration of the sputtered Si and Mo atoms from the mirror surface over the ion kinetic energy range determines the sputtering rate. The number of laser shots needed to remove 1 nm thickness of Si is calculated to be $1.52 \times 10^8$ and for Mo, it is $1.45 \times 10^8$. For a typical multilayer mirror structure, the thickness of a Si/Mo layer pair is 6.9 nm, the ratio of Mo in the layer pair is 0.4, and the peak reflectivity at 13.5 nm is approximately 73% [25]. The peak reflectivity drops from 73% to 66% when the number of the layer pairs is reduced from 40 to 25. It is assumed therefore the required number of laser shots before the mirror reflectivity falls below 66%, will be $1.55 \times 10^{10}$. Here, it is assumed that the distance of the mirror surface from the plasma is 20 cm and the sputtering yields are the same for Sn$^+$ to Sn5$^+$ ions.

Based on the sputtering rate, the calculated operation time is approximately 600 hours with a 7 kHz source repetition rate, as stated in the source requirements. However the
estimated EUV power at IF is lower than the required power when the current tin-doped droplet target is operated at that repetition rate. The laser energy per pulse used is about 100 mJ. With a CE of 2%, the emitted EUV energy into $2\pi$ is 2 mJ. When the source is operated at 7 kHz, the EUV power at the IF will only be 7W assuming $2\pi$ collection and 50 % mirror reflectivity.

To satisfy the power requirement, the laser energy can be increased by, at least, a factor of at least 10 or the repetition rate can be increased by a factor of 10. Assuming that CE of 3% can be achieved, then the EUV power at IF will be 105 W. This is close to the source power requirement of 115 W. Increasing CE may be possible by optimizing the irradiation configuration [14]. Increasing the laser energy is challenging, not only for the laser systems but also for maintaining the optimum CE with the increased laser energy. The laser intensity with the increased laser energy will be greater than the optimum for the current target geometry.

Figure 6.11: The incident ion energy dependencies of the sputtering yields for Si, Mo surfaces. (SRIM calculations)
Increasing the repetition rate can be challenging from the laser viewpoint. It can be considered as a single laser system or multiple laser systems can be temporally multiplexed to achieve higher rates. The target repetition rate of up to 100 kHz is already demonstrated. However, the penalty for increasing laser repetition rate with the same size of target is increased ion emission. The lifetime of the collection optics will be shortened by a factor of 10 at 70 kHz laser repetition rate. Therefore the estimated lifetime of the collector mirror is 60 hours at 70 kHz which is a factor of 500 shorter than the requirement. Thus, ion mitigation with a reduction ratio of at least 500 is necessary to satisfy the lifetime requirement.

6.4 Plasma expansion simulation

As described in Chapter 2, it is possible to calculate and estimate the details of plasma expansion at different laser intensities. The expressions for particle motion and energy transport are presented. The initial target condition is also known in terms of density, size, and concentration of materials. Different levels of approximation can be applied. An isotropic energy deposition and evolution of plasmas can be assumed. It is also possible to include a 3D description of plasma and spatial distribution of laser intensities. The fluid species in the plasma can be individual ion species or an averaged species. For droplet laser plasmas, simulations in one dimensional spherical coordinate agree well with experimental measurements. The electron density profiles are measured using interferometry, and both measurements and simulations agree [58]. The spectrum measured at different laser intensities correspond to the ion populations at the electron temperatures as was predicted [14]. In the following sections, a discussion on the plasma expansion calculated using the simulations are compared with measured ion flux characteristics.
6.4.1 Simplified model of fluid simulations

Tin doped droplet target based plasma generation and expansion are described using a simplified model. The ultimate goal of this model is to describe the details of plasma expansion of a multi-component target. Tin-doped droplet target is an appropriate target, with spherical geometry that can be described in 1D.

The model divides the target into a number of small sections called cells. Each cell has geometrical properties, fluid properties, and plasma properties. The geometrical properties are position, width, area; thus volume. The fluid properties are mass, pressure, density, velocity, and temperature. The plasma properties are a product of species, ionization state, and interactions between species, which supplements the fluid properties. A fluid contains two different species, which are electrons and different ions. An electric field is described as part of the fluid. It is assumed that no magnetic field is applied and the current induced magnetic field is negligible. The concept is illustrated in Figure 6.12.

A C++ code is written to execute the model, and the code declarations and processes are shown in the appendix. Each cell has the properties of position, size, velocity pressure, mass, density, temperature, ionization state, external force, time derivatives of density, velocity, and temperature. The scalar properties of position and size as well as the vector property of velocity can be expressed in 3D. The external force is a vector sum of force due to Lorentz forces and friction forces caused by coulomb collisions with other species. The time derivatives are calculated as described in Equations 2.9 through 2.11. In the energy balance equation, the power transferred to the cell is the sum of absorbed laser energy and energy transfer to ions, which is usually negative. The energy loss due to radiation is not included in this model but it can be implemented with appropriate assumptions, such as blackbody radiation. The ionization state is calculated at each temperature by referring to
the ion population characteristic derived from Equation 2.8. All ionization potentials are obtained from available literature [38, 39].

An example of the initial results for 1D simulation is shown in Figure 6.13. The initial target radius is 20 $\mu$m, and the uniform electron density of $1 \times 10^{28} \text{ m}^{-3}$ and the uniform electron temperature of 300 K are assumed. The ion mass is 118 A.M.U. Laser pulse penetration and absorption at high density region is illustrated at a slightly lower point than the critical density. The electron density peak in the middle of the slope is caused by the local expansion due to the laser energy absorption. Implementation of multiple ion species and a higher dimension description is still underway. It will be interesting to see more detailed calculation and comparison with the experiments.

![Figure 6.12: Concept of cells and properties of the simplified fluid model.](image-url)

Figure 6.12: Concept of cells and properties of the simplified fluid model.
Figure 6.13: Electron density and temperature profiles calculated by the simplified fluid model at 2 ns of 10 ns, 100 mJ Gaussian laser pulse.

### 6.4.2 MEDUSA plasma expansion simulations

MEDUSA [94] is a widely used plasma simulation code [31]. This code calculates the electron temperature and density profiles of laser plasmas. In most of the laser plasma research, the region of the laser absorption and the region of the radiation of interest generated are investigated. These regions are close to the target surface and limited only during the laser pulse duration. In this study, the region of interest is larger and longer in time. In this code simulation, the ion species is only one, which is the average of four different ions. The mass, initial density and the maximum ionization stages are calculated and applied to the simulation.

Figure 6.14, Figure 6.15, and Figure 6.16 show the electron density and temperature transients for different laser intensities. For electron densities, $r^{-3}$ trends are also shown.
The laser pulse duration is 10 ns. The figures show the plasma transients after the laser pulse. There are three distinguished regions, (a) at the center of the plasma, (b) at the front part of the expanding plasma, and (c) the region between the region (a) and the region (b). The electron density and temperature in region (a) continue to remain high as the original target’s density and temperature. This is an artifact of the simulation because the whole target is dissociated by the laser pulse as observed in interferograms [58]. The region (b) propagates at the expansion velocity that is measured by IP. The electron density follows the $r^{-3}$ trend and the temperature remains high compared to that in region (c). This decreasing density and relatively high temperature leads to a low recombination rate, and that is shown in Equation 2.16. The ionization stages in region (b) are seen to be preserved better than in region (c).
Figure 6.14: Medusa calculations of electron density and temperature transient at laser intensity of $1.0 \times 10^{11}$ W/cm$^2$.
Figure 6.15: Medusa calculations of electron density and temperature transient at laser intensity of $2.0 \times 10^{11}$ W/cm$^2$. 
Figure 6.16: Medusa calculations of electron density and temperature transient at laser intensity of $3.0 \times 10^{11}$ W/cm$^2$. 
6.4.3 Comparison between simulations and ion measurements

As calculated previously the high electron temperature region propagates as the plasma expands. This region contains more electrons, which are equal to the charge carried by ions, than the lower temperature plasma region. Comparison between the ion probe signals and the density transients are made. Figure 6.17 shows IP signals and electron density transients at the distance of the IP. The IP signals show the ion flux transients at a distance of 10 cm from the source. Due to the discrete positions of the cells in the simulation, the density transient is less accurate. The density value is averaged over the distance of 99.75 mm to 100.25 mm. The calculation extends to more than 1 µs after the laser pulse peak so that the electron density peak propagates to a distance of more than 10 cm.

The TOFs of the peaks from the IP signals have good agreement with the electron density transients. The high peaks observed in IP for all the measurements are the result of detecting this high density region. Whereas, the electron density transients show little signal in the tail after the peaks. This is caused by the approximation of the mass of the ions which is made in the simulation. The averaged ion expansion is more uniform than the mixture of different masses. The masses of atoms in the target range from 1 A.M.U. to 119 A.M.U. This is confirmed by reconstructing the IP signals from ion energy spectra.

The ion signal reconstruction can be made from ion kinetic energy distributions. The ion signals are calculated in terms of the charge carried by specific ion species at a given TOF. The total ion signals of different elements and the overall ion signals are calculated as the summations of each ion signal. Figure 6.18 (a) and (b) show that the total signals consist of all different elements in the target. It is clear that lighter ions dominate at the beginning of the IP signal and the heaviest ions, tin ions, dominate the tail of the IP signal. This trend is more prominent in the ion signals obtained for plasma at higher laser intensities.
Different ions with different ionization stages are illustrated. Figure 6.19 (a) and (b) show the composition of oxygen and tin ion signals which consist of the all ion species of
different ionization stages. The laser intensity is $2.8 \times 10^{11}$ W/cm$^2$ which is slightly higher than the intensity for the optimum CE, but, they illustrate well the composition of ion signals of different ionization stages. The ion signals of higher ionization stages O$^{5+}$ and Sn$^{5+}$, have peaks at the beginning of the IP signals. The signals from low ionization stages, Sn$^{2+}$, have long tails. This difference in the ionization stages in two different density regions is due to different recombination rates. As seen in Equation 2.16 and as discussed previously, the rate is lower in the higher temperature region than the lower temperature region. The higher ionization stages are the result of lowered recombination processes in the expanding plasma. The kinetic energies of the ions with high ionization stages are high and they have population peaks at high energy regions as seen previously.

By comparing the signal profiles of reconstructed ion signals to the measured IP signals, shown in Figure 6.18, it is clearly seen that the spectrometer measurements preserve the details of the ion species. The ion flux limiting aperture of the ion spectrometer is at a distance of 10 cm from the plasma source which is the typical distance of the ion probe. The spectrometer measures the same ion flux as ion probe even though the ion detector of the spectrometer is placed at a distance of 90 cm from the plasma in a separate vacuum chamber. This comparison asserts the validity of ion energy distributions measured by the ion spectrometer.
Figure 6.18: Reconstructed ion signals of total signals and individual elements at laser intensities of (a) $1.9 \times 10^{11}$, (b) $2.8 \times 10^{11}$ W/cm$^2$. 
Figure 6.19: Reconstructed ion signals at laser intensities of $2.8 \times 10^{11}$ W/cm$^2$. (a) Oxygen ions, and (b) tin ions.
6.5 Summary of ion emission characteristics

Ion emissions from tin-doped droplet plasmas are characterized and the ion flux for different tin concentrations and different laser intensities are obtained. The plasma expansion velocities increase about 50% as the laser intensity is increased by 3 times the intensity for the optimum CE. Quantitative ion spectrometer analysis is made and the all ion energy distributions at different laser intensities are obtained. Large populations of low energy and ions with low ionization stages are observed. The energy distributions are used to estimate the collector mirror lifetime. The lifetime is about a factor of 500 shorter than the EUVL roadmap requirement without any mitigation applied. Small populations of high energy ions with high ionization stages are also observed. Further analysis on IP and ESIEA measurements compared to fluid simulations shows good agreement between the two. The ions with the high ionization stages are preserved in the high electron temperature region in the expanding plasma under low recombination conditions.
CHAPTER 7
MITIGATION

7.1 Introduction

Mitigation, or "inhibition" in a general sense, is the prevention of particles from reaching the collection optics. The term "particles" as used in this chapter is considered to be any form of ejected target material during plasma production causing mirror reflectivity degradation. These include aerosols, neutral atoms, clusters, and ions. All mitigation schemes must not absorb or block useful EUV radiation while they are required to stop, slow down, or repel particles. The mitigation schemes that are investigated extensively in this study are an electrostatic field mitigation scheme, called the Repeller Field, and a Magnetic Foil Trap where a magnetic field is implemented.

7.1.1 Types of mitigation schemes

Many mitigation schemes have been proposed by different research groups in the EUVL source development community. The essential function of mitigation is to reduce the momentum of the particles. One common mitigation scheme is the use of a buffer gas. This mitigation scheme can be realized by just filling buffer gases [95] in the vacuum chamber or making a localized volume with buffer gas referred to as a gas curtain or gas flow [96]. The gases can be ionized to improve the interaction between ions and electrons of the source plasma and those generated in the buffer gases. The ionized gases that have been proposed are secondary plasma [97] and secondary plasma shutter [98]. The particles straggle and
lose momentum due to collisions with the buffer gas atoms, molecules, or ions. However, straggled particles must not reach the collection optics. Otherwise the particles will be deposited on the mirror surfaces and result in the absorption of EUV radiation.

Various types of traps are also commonly used in EUVL source development. The most common is the foil trap [99]. The foil trap structure comprises of a number of thin foils aligned in radial directions from the plasma source so that the radiation pass between the foils. A foil trap does not mitigate very well when used by itself, because particles can pass through between the foils. Particles can be intercepted, if buffer gas is filled between the plasma and the foil trap. The particles collide with the atoms of the buffer gas first and the collisions cause changes in the respective trajectories. Then the particles that collide with the foil surfaces are stacked at the surfaces of the foil trap so that they don’t reach the collection optics. Other types of traps can be implemented by utilizing electric and magnetic fields. Electrostatic field mitigation has been proposed in this study and it is described in the next section. Implementations of magnetic fields have also been proposed [100], where the magnetic field lines are configured to be perpendicular to the ion trajectories so that the ions will be deflected effectively in circular trajectories. The radii of ion motions are determined by the Larmor radius. The field strength must be high enough to deflect heavy ions in low ionization stages such as Xe\textsuperscript{+} and Sn\textsuperscript{+} with their large Larmor radii.

### 7.2 Repeller field mitigation

The Repeller Field approach to debris mitigation was first applied to the water droplet target [76] when it was first found that ion sputtering of a multilayer mirror surface caused reflectivity drop. A Repeller Field was installed between the source and the multilayer mirror witness plate. The reflectivity of the multilayer mirror was monitored by measuring
the EUV emission from the source. The reflectivity lifetime was extended by factor of \( \sim 10 \) with the Repeller Field use. From this result it can be concluded that the field reduced ion flux.

The Repeller Field concept was applied to the tin-doped droplet target as well [91]. The effectiveness of the Repeller Field was evaluated in terms of reduction of the tin aerosol flux. Two witness samples were exposed to the plasma, one with the field applied and another without the field. The amount of tin deposition on the witness plate which was exposed with the Repeller Field was less than that on the plate without the field. The result showed that the field reduced the aerosol flux. These two early results lead to the more detailed analysis on the Repeller Field effectiveness for both ion flux and aerosol flux, which is described in the following two sections.

7.2.1 Effectiveness of repeller field on ion flux

The Repeller Field is found to be capable of extending the mirror lifetime by reducing ion flux but the details of the reduction process are still unknown. It is possible to obtain detailed effectiveness of Repeller Field on ion flux by utilizing the ion diagnostics that are described in previous chapter. Ion probes (IP) and electrostatic ion energy analyzer (ESIEA) are applied to evaluate the effect of Repeller Field on ion flux.

One of the results from the IP measurements is shown in Figure 7.1. The comparison indicates the reduction of the ion flux at the beginning of the signal. In the IP signal with no field applied, the fastest ions appear as a step or a shoulder, which is not observed when the field is applied. It is seen repeatedly by switching on and off the voltage supply. The reduced ion flux is from hydrogen ions, protons, based on the lighter mass than the oxygen’s. However, the reduction is the only apparent difference in the comparison. Once the high
density ion flux reaches the Repeller Field electrode, the effect of the field is not seen. One of the possible explanations for not observing the field effect is the space charge contained in the plasma canceling the field. The voltage drop at the field electrode, which is caused by the charge exchange at the field electrode, is observed when the plasma is generated. The field effects on the oxygen ions are still unknown and therefore the ion measurements with ESIEA are performed.

![Figure 7.1: Comparison of IP signals with repeller field and without the field.](image)

For ESIEA measurements tin-doped targets are applied to see the effectiveness of the field on tin ions as well. In order to see the effect of the field, the analyzer kinetic energy is set to 380 eV. Under the analyzer condition, singly charged oxygen ions, chlorine ions, and tin ions are detected. Figure 7.2 shows that the peaks of these ion species are reduced as the field potential increases. By counting the number of ions contributing to each ion signal peak, reduction ratios of about 200 for oxygen ions, 6 for chlorine ions, and 8 for tin ions are observed. The large reduction ratio of oxygen is the explanation for the extended mirror lifetime in the early experiment. The reduction of ion spectrometer signals are based on the
kinetic energy distributions of individual ion species. The ions detected by the spectrometer have reduced kinetic energies of 380 eV after the Repeller Field. They originally have higher kinetic energies. The chlorine and tin ion species have more populations in higher kinetic energy distribution due to their higher mass than oxygen’s. Higher field potential can reduce the kinetic energy of these Cl and Sn ions. Currently, the voltage applied is the maximum without having discharge between the electrode and other components in the chamber. To reduce ion flux of tin ions, more effective schemes are necessary. The Magnetic Foil Trap mitigation is discussed later in this chapter in terms of high energy tin ions.
Figure 7.2: Ion M/Z spectral analysis on the repeller field effectiveness.
7.2.2 Effectiveness of repeller field on aerosols

It is seen that Repeller Field reduces the aerosol flux which is described in the following sections. This is important in cases where the droplet target positioning is unstable resulting in insufficient heating. When the droplet target is not placed at the desired position in the laser focus, a part of or the entire target is not heated as expected. As a result, a large number of aerosols are created. However, the aerosols that are created in the plasma are charged by the plasma potential [101]. Therefore, it is possible to repel the charged aerosols by the Repeller Field.

Two witness plates are exposed to the plasma source, one with the field applied and the other with no field applied. The amount of the tin deposits on the two samples is compared with the help of Auger electron spectroscopy (AES). Figure 7.3 shows the images of the two witness plates (Si wafer) with surfaces area of 50µm x 50µm, after 3 x 10^4 laser shots, where the distance from the source is 64 mm. Figure 7.3 (a) and (b) are images of the secondary electron images obtained using AES and (c) and (d) are the elemental mapping of the tin signal from the same areas of (a) and (b), respectively. The reduction ratio can be obtained by either counting the number of deposits or calculating the fraction of area covered by the deposits. The numbers of deposits on the samples are 152 and 41 for (a) and (b) respectively. The reduction ratio is 3.7. The fraction of surface coverage is reduced from 65 % to 10 %, where the reduction ratio is 6.5. Due to the fact that aerosols are produced during the source plasma generation, they are charged. The mass to charge ratio depends on the surface area and the mass. It tends to be difficult to mitigate large aerosols which are likely to have large mass to charge ratio. However, the aerosol generation can be controlled by optimizing the laser irradiation conditions, as described in Chapter 5.
Figure 7.3: (a) Secondary electron image of 50µm x 50µm of surface exposed without the repeller field, (b) Secondary electron image of 50µm x 50µm of surface exposed with the repeller field, (c) Auger electron tin elemental mapping of the same area as (a), (d) Tin elemental mapping of the same area as (b).
7.3 Magnetic foil trap mitigation

The Magnetic Foil Trap is a combination of the foil trap mitigation scheme and a magnetic mitigation scheme. The effectiveness of the foil trap mitigation and the transparency of the magnetic field mitigation are great advantages. However, applying large foil structures to the laser plasma source configuration is challenging. The reflected EUV radiation can be blocked by the foil structures around the plasma. A high EUV transmission is achieved by configuring the foil orientation. Also effective reduction of ion flux is achieved by configuring magnetic field lines against the foil structures. An example of the high transmission configuration is shown in Figure 7.4 where a section of the trap and the collector mirror are illustrated. The mitigation processes for different ion species are predicted and ion probe (IP) measurements prove the effectiveness of the mitigation scheme.

Figure 7.4: An example of the magnetic foil trap configuration.
7.3.1 Particle motion in the magnetic field and foil structures

The motion of a charged particle in a magnetic field is described by the Newtonian equation with the Lorentz force,

\[ m\ddot{\mathbf{a}} = q(\dot{\mathbf{v}} \times \mathbf{B}) \]  \hspace{1cm} (7.1)

where \( a \) is the acceleration of the particle, \( q \) is the charge of the particle, \( v \) is the velocity of the particle and \( B \) is the magnetic field. By solving Equation 7.1, the particle motion and the position of the particle as function of time is obtained. In a uniform magnetic field, the motion is a circular motion whose radius is the Larmor radius expressed in,

\[ r_L = \frac{m v}{q B} \]  \hspace{1cm} (7.2)

The orbit of charged high Z material under a typical magnetic field as for instance that obtained from a permanent magnet, is usually large when compared to the size of the foil trap or the source-mirror distances. For example, a singly ionized tin ion with kinetic energy of 1 keV has a radius of 50 cm under a uniform magnetic field of 0.1 T. The ion energy distribution shows that ions with even higher energies are generated. A magnetic field of at least 2 T is necessary to make a circular motion with 10 cm diameter for 4 keV \( \text{Sn}^+ \) ions. It is not realistic to have uniform, high magnetic fields in a large area without blocking the EUV radiation. The Magnetic Foil Trap mitigation scheme utilizes magnetic fields which can be obtained from commercially available permanent magnets. The magnetic field is locally applied in the vacuum space around the source plasma. In such a magnetic field, the motions of the particles are arcs between the source and the mirror.

The deflection of the particle and the foil trap configuration are considered. When a trajectory of a particle is intercepted by a foil surface, the particle is trapped. Let \( \Phi \) be the deflection angle in radians. The distance or radius of the particle position from the source
is R in meters. Some relationships of $\Phi$ and $R$ are shown in Figure 7.5. The trajectories of Sn$^{2+}$ or Sn$^+$ with kinetic energies of 500 eV and 1000 eV are calculated under uniform magnetic field of 0.1 T to illustrate the relationship between $\Phi$ and $R$. The curves in Figure 7.5 can be approximated in linear relationship with a constant slope of $\Phi/R$. The value, $\Phi/R$, represents the deflection rate. Because the deflection rate is nearly constant over a few cm to a few tenths of a cm, the foil trap design criteria can be simplified. Figure 7.5 illustrates the critical ion trajectory with a foil configuration where the ion barely passes through the trap. The kinetic energy of the ion will be the cut off energy of the foil trap. Any ions with smaller kinetic energies than the cut off energy will be deflected more, and thus they will be trapped. In contrast, an ion with higher kinetic energy than the cut off energy will have a smaller deflection rate and it will not be trapped. The cut off energy is determined by the geometry of the foil configuration. The relationship between the foil angle $\Phi_{foil}$ and the foil radius $R_{foil}$ is expressed in,

$$\frac{\Phi_{foil}}{R_{foil}} = \frac{\Phi_{out} - \Phi_{in}}{R_{out} - R_{in}}$$  \hspace{1cm} (7.3)

where the $\Phi_{in}$, $\Phi_{out}$, $R_{in}$, $R_{out}$ are shown in Figure 7.6. To determine if any ion species are trapped or not trapped by the foil structure, the calculated deflection rate $\Phi/R$ is compared to the $\Phi_{foil}/R_{foil}$.

Figure 7.7 shows the deflection rates calculated for several cases. Figure 7.7 (a) illustrates the deflection rates of different ion species where larger mass charge ratio of a singly charged tin ion is most unlikely to be deflected. Figure 7.7 (b) shows exactly the same characteristics with different ion species. With the magnetic field of 0.1 T the foil trap configuration has to have small enough $\Phi_{foil}/R_{foil}$ to trap high energy Sn$^+$ ions. The calculated $\Phi/R$ of Sn$^+$ ion with kinetic energy of 10 keV is about 0.3 rad/m. For example a foil trap configuration with a foil angle of 0.03 rad, a foil inner radius of 2 cm, and a foil outer
radius of 12 cm could trap high energy Sn\(^+\) ions of up to 10 keV. In such a configuration, there will be more than 100 foils over a hemisphere. The obscuration of such a trap can be significant due to the large number of foils. Figure 7.7 (c) shows that the number of foils can be reduced by increasing the magnetic field strength. Under increased magnetic field, for instance 0.5 T, \(\Phi / R\) of Sn\(^+\) ion with kinetic energy of 10 keV is about 1.6 rad/m. With the same radii for the foils in the previous example, foil angle can be relaxed to 0.16 rad. There will be only 20 foils in a hemisphere to trap all of the Sn\(^+\) ions with kinetic energies up to 10 keV. In reality, a magnetic field is not uniform over a large area. Once the magnetic field profile is measured, ion trajectories can be calculated as well as deflection rates. The foil angle can then be determined by the deflection rate as described above.
Figure 7.5: Relationships between $\Phi$ and $R$ under a uniform magnetic field.

Figure 7.6: The illustration of the critical ion trajectory and foils.
Figure 7.7: Ion deflection rates of (a) tin ion species under uniform magnetic field of 0.1 T (b) different ion species under uniform magnetic field of 0.1 T (c) Sn$^+$ under different magnetic field.
7.3.2 Particle motion in non-uniform magnetic field

The magnetic field of the magnetic core described in Figure 4.14 is measured, and the result is shown by Figure 7.8. The pair of foils are perpendicular to the axis of two magnets. The magnetic field measured at the foil axis is used to calculate trajectories of different ion species. Any charged particle motion in a magnetic field can be calculated by the Newtonian equation described by 7.1. In each local point a uniform magnetic field is assumed and in such case the trajectory calculation is completed in exactly the same manner as described in the previous section. In finite time durations an ion experiences a Lorentz force which produces an acceleration of the ion. The acceleration changes the velocity with the finite time duration. A series of calculations provide the total trajectory of an ion with any given kinetic energy and mass-charge ratio.

It is difficult to trap ion species with large mass-charge ratio. In the tin-doped droplet target case, it is Sn$^+$. The deflection rate for this ion, with a kinetic energy of 1.5 keV, is 0.9 rad/m. For a foil angle of 0.1 rad and foil length of 0.1 m, the ion can go through the Magnetic Foil Trap. However, it is expected that most of the oxygen ions with kinetic energies of up to 7 keV will be trapped. There is a maximum to the ion energy in trapping ions. The kinetic energy is the cut off energy. The effectiveness of the mitigation schemes is evaluated with the predicted cut off energies.
7.3.3 Effectiveness of foil trap mitigation

The effectiveness of the Magnetic Foil Trap mitigation scheme is evaluated for the water droplet target case, as well as tin-doped droplet case. The foil angle is set to be 0.1 rad. The inner radius of foils is 38 mm, and the outer diameter is 100 mm. Thus the foil trap captures any ions which have a deflection rate larger than 1.6 rad/m. O⁺ ion with 4 keV can barely go through the mitigation. In addition, the ion energy distribution of O⁺ indicates almost no O⁺ ion has such high energy. However, for Sn⁺ ions, it is expected that some ions pass through and others are captured. For Sn⁺ ions, cut off energy is about 600 eV, and for Sn²⁺ ions, the cut off energy is about 1.8 keV.

Although all oxygen ions are expected to be trapped, a small fraction of oxygen ions are observed in Figure 7.9 (a). The TOF signals indicate that the kinetic energy of the ions detected is about 400 eV. There are two possible explanations for the detection of these low energy ions. One is the finite plasma source size. The calculation of cut-off kinetic energies
assumes a point source for the ion generation. Another is the scattering of ions. While the plasma is expanding from the hot dense plasma phase, highly charged ion collisions can add slight deflection to the trajectories.

Figure 7.9: IP measurement with magnetic foil trap for (a) water droplet target case, (b) tin-doped droplet target case.
As expected previously, higher energy tin ions are detected as shown in Figure 7.9 (b). The small signal peak with mitigation gives TOF signal measurements of about 1.6 $\mu$s, which corresponds to a kinetic energy of 2 keV. Low signal amplitude of scattering ions is also detected. The reduction factors for the two different targets are 20 for water droplet, and 6.5 for tin-doped droplet target, which are calculated by integrating the area of these signals. Higher reduction ratios can be obtained by configuring a small deflection angle, in other words, a smaller foil angle and/or large distance between the inner radius and outer radius of the foil. It can also be obtained by increasing the magnetic field.

### 7.4 Combination of two mitigation schemes

In order for tin-doped droplet targets to satisfy the EUVL source lifetime requirement, a large factor of ion flux reduction is necessary. As described in the previous chapter, the lifetime requirement must be met with a reduction in ion flux of at least 500. The factors of reductions of Repeller Field and Magnetic Foil Trap each range from 5 to 20. When the two mitigation schemes are combined together, it is expected that the reduction factor will be around a hundred. Further reduction can be achieved with minor modifications to both schemes. However, detecting reduced ion flux becomes difficult. As demonstrated in the following sections, IP is not sensitive enough to detect reduced ion flux. Instead, a channel electron multiplier is utilized to realize an amplified ion probe. It is discussed in the later section that the ion flux reduction that is obtained with combined mitigation schemes is sufficient to satisfy the lifetime requirement.
7.4.1 Detection limit of ion flux

Here an improved ion mitigation is described when the Repeller Field is modified to have higher voltage driving capacity. A power supply that can provide higher voltage and higher current is used. The field electrode is encapsulated to reduce discharge between high voltage electrodes and other components in the vacuum chamber. It is isolated with a PVC tube and has ground electrodes, as shown in Figure 7.10. The electric field is principally contained to between the ground electrodes. With short distances between the ground electrodes and the high voltage electrode, a higher breakdown voltage is expected due to the concept of Paschen’s law [102].

Figure 7.10: Photo and schematic of modified encapsulated repeller field mitigation.
Ion probe measurements were carried out with this modified Repeller Field for water droplet targets. The laser intensities for this measurement, for the modified Magnetic Foil Trap, and the combination of two mitigation schemes are around $3 \times 10^{11} \text{ W/cm}^2$. These intensities were too high to have the highest CE. However, the generation of higher energy ions is preferred for evaluating the effectiveness of the schemes. Figure 7.11 shows improved reduction compared to the previous configuration which is shown in Figure 7.1. Higher ion flux can be reduced by a factor of about four. This modified Repeller Field is used with another modified magnetic foil mitigation.

A new configuration of the Magnetic Foil Trap was applied with a smaller deflection rate of 0.5 rad/m. The foil angle was 0.05 rad, and the distance between the inner radius and the outer radius is 10 cm. The magnetic field itself was unchanged. The cut off energy for Sn$^+$ was 5 keV, and for Sn$^{2+}$ was 20 keV. IP measurements were carried out with the modified Magnetic Foil Trap for tin-doped droplet targets which is shown in Figure 7.12. A large reduction in ion flux was observed. Peaks caused by higher energy tin ions were not observed by IP. However the signal level was close to the minimum detection level of IP and the oscilloscope. Therefore the amplified ion probe is utilized.
Figure 7.11: IP signal comparison between different field potentials of the modified Repeller Field.

Figure 7.12: IP signals on the modified Magnetic Foil Trap.
7.4.2 Demonstration of sufficient ion flux reduction

The ion flux is measured by the amplified ion probe described in Figure 4.10. Three ion signals, with no mitigation but a foil trap, with foil trap and magnetic field, and with Magnetic Foil Trap and Repeller Field are compared in Figure 7.13. The signals are amplified by a factor of $10^7$ with a -3 kV bias. The ion signal with the foil trap shows a dip at 2.3 µs. The ion flux would be highest where the dip is, according to all the previous measurements. The amplified ion signals can be suppressed by gain reduction due to excess instant signal current and detection efficiency reduction with too high ion density at the detector surface. The dip appears regardless of the biasing voltage. Thus the ion flux is too high with the limiting aperture of 2 mm and the CEM distance from the plasma. However, detection levels of the ion flux are barely adequate when mitigation schemes are installed. Very low ion flux is measured with mitigation schemes. The remaining ion signals only have a small peak when mitigation schemes are installed. The corresponding ion kinetic energy is about 10 keV for tin ions. It can be further reduced by increasing the magnetic field.

![Figure 7.13: Amplified ion probe signals with two mitigation schemes installed.](image-url)
With the combined mitigation configuration of modified Repeller Field and Magnetic Foil Trap, the erosion rate is calculated based on the ion energy distributions. Although sputtering yield for higher incident tin ions is high, the populations of these high energy ions are very small. The lifetime estimations which are described in Chapter 6 are applied here as well. The estimated erosion rate is $7.7 \times 10^{10}$ shots for 1 nm sputtering of Si, and $6.5 \times 10^{10}$ shots for 1 nm sputtering of Mo. Based on these values, $5.0 \times 10^{11}$ shots will be needed to remove one layer pair. Thus, the mirror reflectivity lifetime will be $7.5 \times 10^{12}$ shots, which is equivalent to the time duration of 30,000 hours at 70 kHz source operation. It is enough to satisfy the EUVL source lifetime.

### 7.4.3 Neutral atom mitigation

One insight gained by the measurements described in the previous section is that there is no signal detected from the neutral atom flux. The CEM can detect neutral atoms. The Repeller Field cannot manipulate neutral atoms. As plasma expands and cools down, the ionization stages decrease. The kinetic energies of neutrals would be similar to that of singly charged tin ions. Thus, the high-energy ion signal is not likely due to neutrals. The whole target is ionized by the laser pulse and ions are deflected by the magnetic field of the mitigation. When singly charged ions are recombined with electrons, they are already deflected enough so that they are trapped by the foil surfaces. Therefore, the Magnetic Foil Trap demonstrated mitigation effects on neutral atoms.

### 7.5 Summary of mitigation

The Repeller Field and Magnetic Foil Trap mitigation schemes are evaluated in terms of both ion flux and aerosol flux. The Repeller Field reduces aerosol flux effectively,
but reduces ion flux less effectively. The charges in the plasma can easily cancel the field. If the field is encapsulated so that a higher voltage can be applied, ion reduction is improved. The Magnetic Foil Trap mitigation reduces ion flux very effectively but passes a small amount of scattered ions. The two mitigations are combined in order to be more effective for ion flux reduction. Only a small amount of high energy tin ions, more than 10 keV, can pass through the two mitigation schemes. The estimated erosion rate is small due to the small population of the high energy ions. With the implementation of the two methods described, it is concluded that the multilayer mirror lifetime can be extended to meet the EUVL source lifetime requirement.
CHAPTER 8
CONCLUSION AND FUTURE WORK

8.1 Conclusion

As described in the previous chapter, tin-doped droplet laser plasma sources can satisfy the EUVL source lifetime requirements with the use of the two mitigation schemes described here. A separate program demonstrated high CE [59]. The EUV power delivery can be achieved with the use of high repetition rate lasers. Therefore, it is expected that this target configuration will satisfy the most challenging aspects of the source requirements; power and lifetime. To support this conclusion this study discusses the debris emission characteristics and mitigation effectiveness. Aerosols are observed on witness plates and identified as tin which are generated in the target under insufficient laser heating. The generation of aerosols is minimized by optimizing the laser intensities. Ion kinetic energy distributions for individual ion species are characterized for different laser intensities. The distributions are used with surface sputtering simulation code to estimate the erosion rates of multilayer mirrors. The estimated lifetime is a factor of about 500 shorter than the requirement with no mitigation techniques applied.

Two mitigation schemes are evaluated in reducing aerosol flux and ion flux. The combination of these two mitigation schemes demonstrated a sufficient reduction in ion flux. This study also discusses mass limited targets, the mechanisms behind mirror degradation, fluid properties of laser plasmas, the instrumentation for debris detection and analysis to validate all the measurements and analysis.
8.2 Future work

There are some uninvestigated areas which relate to this study. One of them is a real erosion rate measurement by exposing multilayer surfaces with long term laser plasma source operations. Reliable angular distribution profiles of not only ion emission but also EUV radiation are unavailable. Tin ion implantation can be possible and the impact of this on the reflectivity lifetime is unknown. The Magnetic Foil Trap is effective in mitigating ions, but the radiation characteristics from the plasma may be affected under the magnetic field due to the electron cyclotron motion that tends to prohibit electron-ion collisions. The plasma density and temperature transient can be measured and compared with predictions by fluid simulations. It might be possible to manipulate the plasma density and temperature before and after the targetlaser interaction in order to lower the kinetic energies transferred to ions. These areas can be investigated with new facilities and raise other research topics and areas. The following sections discuss some of these topics.

8.2.1 High repetition rate laser plasmas

The current experimental facility is limited by the laser repetition rate and long term target delivery stability. Long exposure experiments are challenging because the repetition rate of the laser available is only 100 Hz, which is the highest repetition laser system with appropriate parameters in the laboratory. With a higher repetition rate laser system, real time measurements of the erosion rate can be obtained.

It is meaningful not only to measure erosion rate, but also to produce high EUV power. It is necessary to collect the emitted radiation with large solid angle mirrors to realize an EUV light source suitable to operate with micro exposure tools. The droplet laser
plasma source is small and it can be considered as point source so that imaging, exposure of materials, and microscopy can be integrated with the high power source.

8.2.2 Target stabilization systems

Even if long term operation of the current laser is possible, it still needs an operator to control target positioning for the duration of operation. The target supply and unused target retrieval can be solved relatively easily. However, the slow drifting of target-laser synchronization has to be adjusted. A separate effort is made to realize an intelligent target positioning with 3D feedback in atmosphere which can be integrated into the target chamber. If it is integrated with a high repetition laser system, a reliable EUV light source facility will be realized.

By doping different materials with different concentrations into the droplet target, the radiation from the plasma can be broadened with a mixture of many spectral peaks. Different research areas can utilize such a single source configuration. It is convenient to have a local short wavelength light source other than the synchrotron facilities. It can also be used as a high energy and highly charged ion source. Different from the EUVL source collector mirror configurations, ion emissions can also be useful. The laser irradiation conditions can be varied for such a target. By varying the laser intensity, the plasma temperature changes as well as radiations and ionization stages. All these ideas rely on stable target positioning.

8.2.3 Radiation study under magnetic field existence

In the long history of plasma generation and confinement, different plasma properties under magnetic fields are often observed. The collision frequency in hot dense plasma is much higher than the electron cyclotron frequency. The effects of the magnetic field may be too small to observe. However, the gas discharge pinch plasmas are relatively long-lived. Any
CE improvement with the magnetic field in laser plasmas can enable cheaper EUVL light sources. Any radiation confinement can reduce collection angle, as well. Reducing the size of the collector mirror can reduce the cost of EUVL sources. Utilization of grazing incidence mirrors with confined laser plasmas may be possible.

8.2.4 Temporary and spatially resolved spectroscopy

For better understanding of the plasma physics of the droplet laser plasmas, the combination of simulations and diagnostics are very powerful tools. The simulations are typically bundles of calculations at different positions and different times. Most of the diagnostics including spectroscopy are collecting information over specific time duration. Either temporal resolution or spatial resolution of spectroscopy can provide more detailed plasma parameters than time and space averaged spectroscopy. The comparison between simulations and measurements are then used to improve the plasma modeling. Improved modeling can enhance control of experimental parameters such as laser energy, pulse duration, wavelength, and target size.

8.2.5 Pre-pulse and post pulse heating

Pre-pulse is a small laser pulse which is applied just before the large intensity laser pulse arrives at the target. This scheme is shown by researchers to increase CE [37, 62] as it creates a low-density gradient plasma before the main plasma is created. The pressure gradient produces the momentum for plasma expansion. Pressure is proportional to the product of density and temperature. A smaller density gradient at a constant temperature produces less momentum of expansion. Smaller expansion velocities are expected in the presence of pre-pulse.

Similar schemes can be applied but after the laser interaction. This is a unique strat-
egy that can be applied with Magnetic Foil Trap mitigation. The lower electron temperature in the majority of the plasma region after the laser pulse leads to high recombination rates. A post pulse with a small laser energy can increase the temperature so that recombination processes are reduced. The Magnetic Foil Trap can capture ions with higher ionization stages easier than lower ones. Singly ionized tin ions are the most difficult to capture. Thus a post pulse can enhance the effectiveness of the mitigation schemes.
APPENDIX A
ION KINETIC ENERGY DISTRIBUTIONS
All the ion kinetic energy distributions that are detected by ESIEA spectrometer are shown. Some selected distributions are presented in the thesis.

![Ion energy distribution H⁺](image)

Figure A.1: Ion energy distribution of H⁺.
(a) Ion energy distribution of O$^+$.  
(b) Ion energy distribution of O$^{2+}$.  
(c) Ion energy distribution of O$^{3+}$.  
(d) Ion energy distribution of O$^{4+}$.  
(e) Ion energy distribution of O$^{5+}$.

Figure A.2: Ion energy distributions of different Oxygen ions.
Figure A.3: Ion energy distributions of different Chlorine ions.

(f) Ion energy distribution of Cl$^+$.  
(g) Ion energy distribution of Cl$^{2+}$.  
(h) Ion energy distribution of Cl$^{3+}$.  
(i) Ion energy distribution of Cl$^{4+}$.  
(j) Ion energy distribution of Cl$^{5+}$.  

144
Figure A.4: Ion energy distributions of different Tin ions.
APPENDIX B
SIMPLIFIED FLUID DESCRIPTION OF PLASMA SIMULATION
B.1 Class declaration

The class declarations of the program code for the plasma fluid simulation which is described in Chapter 6 are shown. The code is currently built in one dimension spherical coordinate. It has capabilities of being extended into three dimensions, which can be Cartesian, polar, and cylindrical.

```cpp
#define MAX_CELL_NUMBER 1024
#define MAX_ION_SPECIES 8

struct Coordinate {
    double x;
    double y;
    double z;
    double r;
    double theta;
    double phi;
};

class Cell {
    public:
        Cell();
        ~Cell();
        Coordinate position; //m
        Coordinate size; //m
        Coordinate velocity; //m/s
        double volume; //m3
        double Area; //m2
        double EnergyDeposited; //W
        double pressure; //N/m2
        double MassAMU; //AMU
        double density; //m-3
        double temperatureK; //K
        double temperatureEV; //eV
        double TransferEnergy; //J/m3
        double ExternalForce; //N
        double IonizationState; //Z -1,0,1,2,...
        double DiffDensity; //delta n
        Coordinate DiffVelocity; //delta v
        double DiffTemperatureK; //delta T
    private:
};

#define MAX_CELL_NUMBER 1024
#define MAX_ION_SPECIES 8

class Fluid {
    public:
        Fluid();
        ~Fluid();
        Fluid();
    private:
};
```
int nMaxCell;
int nMaxIons;
int CellOrderElectrons[MAX_CELL_NUMBER];
int CellOrderIons[MAX_ION_SPECIES][MAX_CELL_NUMBER];
Cell Electrons[MAX_CELL_NUMBER];
Cell Ions[MAX_ION_SPECIES][MAX_CELL_NUMBER];
double ElectricField[MAX_CELL_NUMBER];  // V/m
bool Process1DS(double DeltaT, double TimeStamp); // 1 dimension spherical
void SummarizeCell1D();
void ExportParameters(double TimeStamp);
double AmbientPressure;
double AmbientTemperatureK;
private:
};
B.2 1D Process routine (method)

The class "Fluid" has the following method that processes dynamics of the fluid with a given time step. The method is specialized for a spherical coordinate and includes calculations of divergence of the velocities. However it has no advanced conditional functions that check negative density, temperature, cell size and so on.

```cpp
bool Fluid::Process1DS(double DeltaT, double TimeStamp)
{
    bool RetValue=true;

    double SolidAngle=4*M_PI;
    double CoulombLogarithm=10;
    double NuEI_1=4.0*sqrt(2.0/MassElectron*M_PI)*pow(eChargeUnit,4)*CoulombLogarithm/3.0;
    //For first part friction coefficient
    double Alpha_1=4.0*sqrt(2.0*M_PI)*pow(eChargeUnit,4)*CoulombLogarithm/3.0;
    //Process
    for(int idx=1; idx<nMaxCell; idx++){
        //Electrons
        Electrons[idx].TransferEnergy=0;
        for(int idxIon=1; idxIon<nMaxIons; idxIon++){
            double NuEI=NuEI_1*Electrons[idx].density*Ions[idxIon][idx].density
                     *pow(Ions[idxIon][idx].IonizationState,2)
                     /(kBoltzmann*Electrons[idx].temperatureK
                     *sqrt(kBoltzmann*Electrons[idx].temperatureK));
            Electrons[idx].TransferEnergy-=3.0/2.0*kBoltzmann*NuEI
                                         *(Electrons[idx].temperatureK-Ions[idxIon][idx].temperatureK);
        }
        double GradP=(Electrons[idx+1].pressure-Electrons[idx-1].pressure)/Electrons[idx].size.r;
        //Electric Field
        ElectricField[idx]=-GradP/(Electrons[idx].density*eChargeUnit);
        //Energy balance
        double DivV=1/pow(Electrons[idx].position.r,2)
                     *(pow(Electrons[idx].position.r,2)*Electrons[idx].velocity.r
                     -pow(Electrons[idx-1].position.r,2)*Electrons[idx-1].velocity.r)
                     /Electrons[idx].size.r;
        Electrons[idx].DiffDensity=-Electrons[idx].density*DivV*DeltaT;
        //Momentum transfer
        Electrons[idx].DiffTemperatureK=
                     2.0*DeltaT/(3.0*Electrons[idx].density*kBoltzmann)
                     *(-Electrons[idx].pressure*DivV
                     +Electrons[idx].TransferEnergy
                     +Electrons[idx].EnergyDeposited/DeltaT);
        //Ions
        for(int idxIon=0; idxIon<nMaxIons; idxIon++){
            double NuEI=NuEI_1*Electrons[idx].density*Ions[idxIon][idx].density
                     *pow(Ions[idxIon][idx].IonizationState,2)
                     /(kBoltzmann*Electrons[idx].temperatureK
                     *sqrt(kBoltzmann*Electrons[idx].temperatureK));
            Ions[idxIon][idx].TransferEnergy=3.0/2.0*kBoltzmann*NuEI
                     *(Electrons[idx].temperatureK-Ions[idxIon][idx].temperatureK);
            //Particle number conservation
            double DivV=1/pow(Ions[idxIon][idx].position.r,2)
                     *(pow(Ions[idxIon][idx].position.r,2)*Ions[idxIon][idx].velocity.r
                     -pow(Ions[idxIon][idx-1].position.r,2)*Ions[idxIon][idx-1].velocity.r)
```

/Ions[idxIon][idx].size.r;
Ions[idxIon][idx].DiffDensity=-Ions[idxIon][idx].density*DivV*DeltaT;
//Momentum transfer
GradP=(Ions[idxIon][idx+1].pressure-Ions[idxIon][idx-1].pressure)/Ions[idxIon][idx].size.r;
//Friction force
double MassReduced;
double Alpha=0;
for(int idxIon2=0; idxIon2<nMaxIons; idxIon2++){
    Alpha+=Alpha_1/sqrt(MassReduced)*pow(Ions[idxIon][idx].density*Ions[idxIon][idx].IonizationState,2)*MassReduced*(Ions[idxIon2][idx].velocity.r-Ions[idxIon][idx].velocity.r);
}
Ions[idxIon][idx].DiffVelocity.r=DeltaT/(Ions[idxIon][idx].density*Ions[idxIon][idx].MassAMU*MassProton)*(-GradP-Alpha+Ions[idxIon][idx].ExternalForce);
//Energy balance
Ions[idxIon][idx].DiffTemperatureK=2.0*DeltaT/(3.0*Ions[idxIon][idx].density*kBoltzmann)*(-Ions[idxIon][idx].pressure*DivV+Ions[idxIon][idx].TransferEnergy);
}
//Post process
//Process Time derivatives
for(int idx=1; idx<nMaxCell; idx++){
    Electrons[idx].temperatureK+=Electrons[idx].DiffTemperatureK;
    if(Electrons[idx].temperatureK<0){
        cout << "negative electron temperature at " << idx << endl;
        Electrons[idx].temperatureK=1e-30;
        RetValue=false;
    }
    Electrons[idx].temperatureEV=Electrons[idx].temperatureK/KperEV;
    for(int idxIon=0; idxIon<nMaxIons; idxIon++){
        Ions[idxIon][idx].temperatureK+=Ions[idxIon][idx].DiffTemperatureK;
        if(Ions[idxIon][idx].temperatureK<0){
            cout << "negative ion temperature at " << idx << endl;
            Ions[idxIon][idx].temperatureK=1e-30;
            RetValue=false;
        }
        Ions[idxIon][idx].temperatureEV=Ions[idxIon][idx].temperatureK/KperEV;
        Ions[idxIon][idx].density+=Ions[idxIon][idx].DiffDensity;
        if(Ions[idxIon][idx].density<0){
            cout << "negative ion density at " << idx << endl;
            Ions[idxIon][idx].density=1e-30;
            RetValue=false;
        }
        Ions[idxIon][idx].velocity.r+=Ions[idxIon][idx].DiffVelocity.r;
    }
    Electrons[idx].density=0;
    Electrons[idx].velocity.r=0;
    for(int idxIon=0; idxIon<nMaxIons; idxIon++){
        double Zn=Ions[idxIon][idx].IonizationState*Ions[idxIon][idx].density;
        Electrons[idx].density+=Zn;
        Electrons[idx].velocity.r+=Zn*Ions[idxIon][idx].velocity.r;
    }
    Electrons[idx].velocity.r=Electrons[idx].velocity.r/Electrons[idx].density;
}
//Calculate motion
for(int idx=1; idx<nMaxCell; idx++){
    Electrons[idx].position.r+=Electrons[idx].velocity.r*DeltaT;
    for(int idxIon=0; idxIon<nMaxIons; idxIon++){
        Ions[idxIon][idx].position.r+=Ions[idxIon][idx].velocity.r*DeltaT;
    }
}

//Calculate cell size, area, volume, pressure
for(int idx=1; idx<nMaxCell; idx++){
    Electrons[idx].size.r=Electrons[idx].position.r-Electrons[idx-1].position.r;
    if(Electrons[idx].size.r<0){
        RetValue=false;
        cout << "negative cell size at " << idx << endl;
    }
    Electrons[idx].Area=SolidAngle*pow(Electrons[idx].position.r,2);
    Electrons[idx].volume=Electrons[idx].size.r*Electrons[idx].Area;
    for(int idxIon=0; idxIon<nMaxIons; idxIon++){
        Ions[idxIon][idx].size.r=Ions[idxIon][idx].position.r-Ions[idxIon][idx-1].position.r;
        if(Ions[idxIon][idx].size.r<0){
            RetValue=false;
            cout << "negative cell size at " << idx << endl;
        }
        Ions[idxIon][idx].Area=SolidAngle*pow(Ions[idxIon][idx].position.r,2);
        Ions[idxIon][idx].volume=Ions[idxIon][idx].size.r*Ions[idxIon][idx].Area;
        Ions[idxIon][idx].pressure=Ions[idxIon][idx].density*kBoltzmann*Ions[idxIon][idx].temperatureK;
    }
    Electrons[idx].density=0;
    for(int idxIon=0; idxIon<nMaxIons; idxIon++)
    
        Electrons[idx].density+=Ions[idxIon][idx].IonizationState*Ions[idxIon][idx].density;
    
    Electrons[idx].pressure=Electrons[idx].density*kBoltzmann*Electrons[idx].temperatureK;
}

if(RetValue==false)
    ExportParameters(TimeStamp);
return RetValue;
REFERENCES


[66] Matsunari, S., Aoki, T., Gomei, Y., Terashima, S., Takase, H., Niibe, M., Kakutani, Y., "Lifetime estimation and improvement of capping layer on multilayer mirror for


[85] Online article on sensors, article found at www.sensormag.com/articles/1000/68/main.shtml.


