Spectroscopic studies of the Sn-based droplet laser plasma EUV source

C-S. Koay, K. Takenoshita, E. Fujiwara**, M. Al-Rabban[a], M. Richardson*
Laser Plasma Laboratory, School of Optics: CREOL & FPCE, University of Central Florida;
[a] Qatar University, Qatar

ABSTRACT

We have previously reported encouraging results with a new type of laser plasma source. As a radiation source at 13.5nm spectral band, tin has several advantages over xenon, not the least of which is the number of ion species within the plasma that contribute to the in-band emission.

In this paper we report results from spectroscopic measurements of the laser plasma emission from 12 - 19nm from this target, together with hydrodynamic code simulations of the source, towards developing a suitable laser plasma source for EUV lithography.

Keywords: Sources, EUV, laser-plasmas, tin plasmas,

1. INTRODUCTION

EUV lithography (EUVL) technology will allow mass production of computer chips at 32nm nodes and below. Two of the important issues mentioned in the EUV source development roadmap are conversion efficiency and debris. Both laser and discharge plasma sources are being developed to make EUVL successful—a stable, debris-free, light source producing collectable in-band (2%) emission at ~13.5 nm with power levels[1] above 100W at an intermediate focus.

For a laser produced plasma (LPP) source to succeed in this application, it must operate continually for periods of ~1 year at repetition rate of 5-10 kHz with a pulse-to-pulse stability of <2%. Its scheme must also prevent the large-NA (>0.25) collection optics from suffering deleterious effects of target debris in long-term operation. The conversion efficiency from the laser light to useful EUV emission must be sufficiently large to (i) provide the projected required collectable power levels with viable commercial lasers and (ii) permit the overall cost of the source, including the laser, to remain within economic models of the overall EUV lithography stepper tool.

A number of LPP schemes have been investigated for EUVL, including high density, pulsed or continuous cluster targets[2,3], liquid jets[4,5] or droplets[6] of liquid xenon, and water droplet[7-11] and jet[12] targets. Since 1992, we have been investigating the use of microscopic liquid droplets at high repetition-rate as limited-mass laser plasma targets[7, 9]. Droplet targets have demonstrated extended operating lifetimes without significant debris contamination[13]. Both the xenon and the water LPP sources showed conversion efficiencies to in-band radiation of <0.8% in 2π sr, a value that makes achieving the requirement for sufficient power for EUV lithography difficult with the available laser technology.

Laser plasma source using tin as a target material has been known to provide high conversion efficiency for in-band emission at 13.5nm since the early experiments with solid tin target[14]. However, it was thought unsuitable for EUV lithography because of the debris it produces when used in metallic form. The latter led to the development of xenon EUV sources as this was considered to be a better choice over tin because of the debris issue, although for xenon, only one ion species within the plasma effectively contributes to the in-band emission at 13.5 nm as compared to tin, which has many[15-17].

We have long proposed the need for the use of mass-limited targets as laser plasma EUVL sources[7]. Our development of the tin-doped droplet target using this concept can enable a high power and debris-free EUV source[18-20]. Here we report the progress of our studies on a tin material target which demonstrates in-band conversion efficiencies in excess of 1%.

---

*email: mcr@creol.ucf.edu, Fax: +1-407-823-3570
** Present address: Himeji University, Japan

Emerging Lithographic Technologies VIII, edited by R. Scott Mackay,
Proceedings of SPIE Vol. 5374 (SPIE, Bellingham, WA, 2004)
0277-786X/04/$15 · doi: 10.1117/12.541575

This will enable >45W (into 2π sr within a 2% spectral bandwidth at 13.5 nm, at the source) of useful EUV source powers using high power Nd:laser technology[21]. Companion papers report detailed quantitative studies of the debris and development of debris inhibition techniques for the source[22], and summarize its spectroscopic advantages over xenon[23].

2. EXPERIMENTAL FACILITY

The facility for studying EUV radiation at the Laser Plasma Laboratory consists principally of a precision Nd:YAG laser, a target vacuum chamber and various EUV diagnostics. The cylindrical target chamber consists of 12 vacuum ports that are positioned around the body of the cylinder, allowing various EUV diagnostic to be connected the chamber. The axes of all the ports intersect at the center of the chamber, where usually a target is positioned during an experiment. Fig. 1 shows a typical experimental setup, depicting a flat-field spectrometer and a Flying Circus instrument positioned at angles 90^o and 30^o respectively from the input laser beam axis.

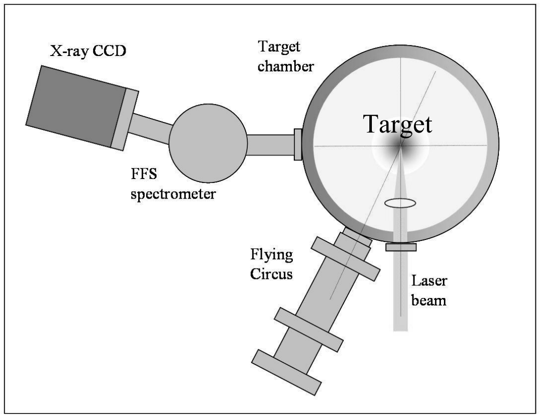

Figure 1: Typical experimental setup.

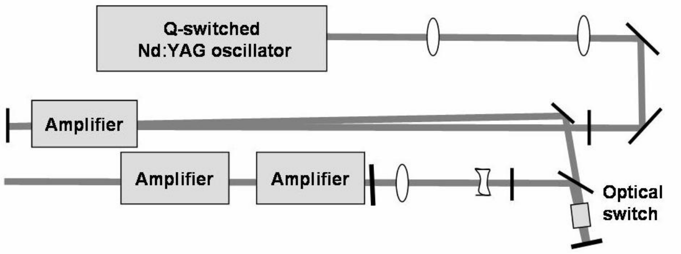

Figure 2: Layout of the Nd.YAG laser used for the experiment showing the master oscillator and three amplifiers.

The laser used in the studies is a special, Q-switched Nd:YAG oscillator-amplifier laser system (λ = 1064 nm) operating at 1Hz, producing up to 1.6J per pulse, with a 11.5ns (FWHM) pulse duration. The laser consists of a master oscillator and three amplifier modules (Fig. 2). The laser beam makes two passes through the first amplifier, followed by single pass through the remaining amplifiers. The beam quality of laser output has an M^2 ~1.5, Gaussian fit correlation ~0.93, and it can be focused to a minimum spot size of 35 μm diameter with an f =10 cm lens. Fig. 3 shows the far field beam profile measurement made by using a Spiricon, as well as a detailed mapping of the focal region. This detailed mapping of the focal region allows an accurate determination of laser power density irradiating a target.

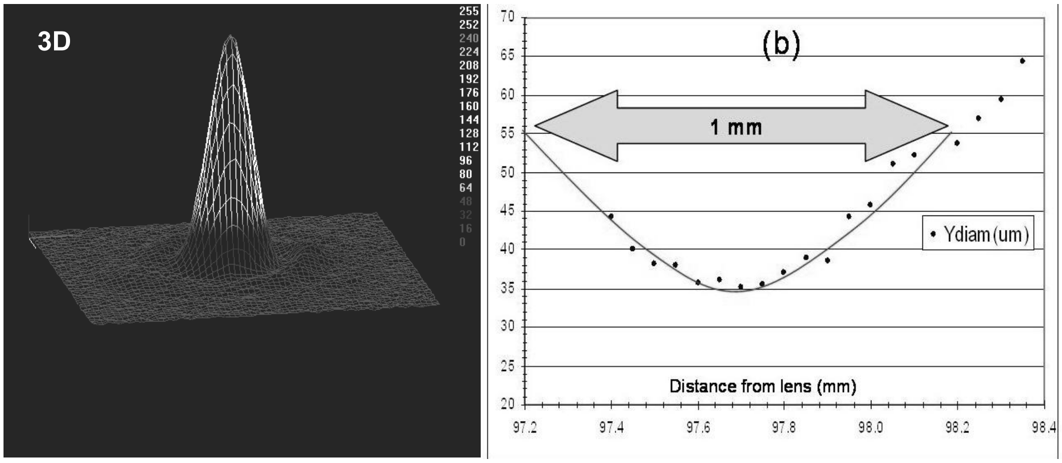

Figure 3: Laser beam performance and detailed mapping of the focal region for an f = 10cm lens.

Diagnostics

High resolution spectroscopic studies of the EUV emission from the source are made by using a flat-field reflective grating spectrometer. The flat-field spectrometer (FFS) uses a 1200 lines/mm, gold coated, variable spaced reflective grating in a configuration reported previously[24]. A slit is used to collimate the light from the source to the grating with 3^o grazing incidence angle. The slit-to-grating and grating-to-image-plane distances are 23.7 cm and 23.5 cm respectively. A 0.5 μm thick, freestanding Zr metal filter is used in the spectrometer to select wavelengths from 6.5 – 16.8 nm (FWHM). A back-thinned x-ray CCD camera is used to record the dispersed spectrum[25].

Although the laser plasma source emits a range of radiation, from the visible spectrum to x-ray, only a particular spectral band (centered at ~13.5nm) is useful for EUV lithography. The amount of emitted energy from the source, within this spectral band, was measured with the so called Flying Circus[26] (FC) detector. The FC is a narrowband EUV diagnostic comprising a calibrated curved normal incidence multilayer mirror and a Zr filtered AXUV–100 photodiode (IRD, USA). The Mo-Si multilayer spherical mirror collects light from the source; a fresh mirror typically has a peak reflectivity of ~69% around 13.5nm, with a narrow band (~3.7% FWHM). The photodiode has a spectral responsivity of ~0.23 A/W at 13.5 nm, and it is reversed bias at 26 volts to ensure linearity. The transmission at 13.5 nm for a 0.5 μm thick Zr metal filter is ~18%.

Mass-limited target

We utilized the concept of a limited mass target to minimize the effects of target debris produced from laser plasma interaction. This concept aims toward limiting the mass of the target to one whose mass, and size, approximates that of simply the number of atomic radiators required for emission. In this way, the number of neutral target atoms generated can be controlled, and the production of high velocity solid particles emanating from the target can hopefully be avoided completely.

The present targets are produced in the form of small spherical droplets ~30 μm diameter, with small amount of tin mixed in low-Z material. The amount of tin in each droplet target is $\sim10^{13}$ tin atoms, and the number can be controlled by changing the target composition. These tin-doped droplet targets are produced from a capillary dispenser. When driven through a nozzle by a piezo-electric module at a high frequency, a thin chain of droplets is produced (Fig. 4). Producing the droplets at high frequencies of 20 - 200 kHz is advantageous because, if each droplet is be heated by a laser pulse from a high power laser to produce EUV, then the emitted power can be scaled upward to meet the power requirement for EUV lithography. When a target is synchronized to a laser pulse, the stability of the high velocity (typically 2×10^4 cm/s) droplet target in the target region is about 3 μm at distances of ~10 mm from the nozzle exit.

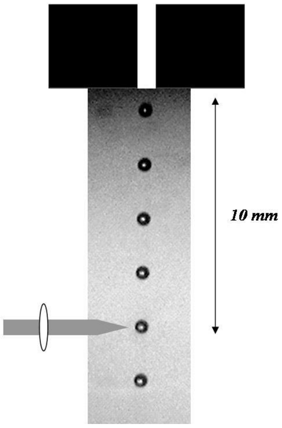

Figure 4: Thin chain of droplet targets with the laser beam focused on a droplet.

During experiments, the target was located centrally in the 45 cm diameter vacuum chamber, which was operated at pressure below 10^{-3} Torr with a turbo-drag pump backed with a roughing pump. At this pressure, absorption of EUV radiation by the air inside the target chamber is <1% for distance of 100 cm.

3. SPECTRA AND STUDY OF CONCENTRATION

High resolution EUV spectra of the tin-doped droplet target laser plasma source have been obtained by using the FFS for wavelength range of 12 – 19 nm. Studies of the effects of tin concentration on the emission spectra have been made for three tin concentrations: 7%, 21% and 27% tin by mass. Target concentration is quoted as "% tin by mass", which is equal to the mass of tin in the target divided by the total mass of the target. The results depicted in Fig. 5 show that for the same laser pulse energy and intensity, the in-band EUV emission increased with increasing tin concentration. The spectral shape is typical of the tin-doped droplet target source, where the spectral peak at 13.5nm is an unresolved transition array (UTA) arising from superposition of an enormous number of emission lines, primarily due to $4p^64d^N \rightarrow 4p^54d^{N+1} + 4p^64d^{N-1}4f$ transitions from Sn^{8+} to Sn^{11+} ion stages overlapping in energy[15].

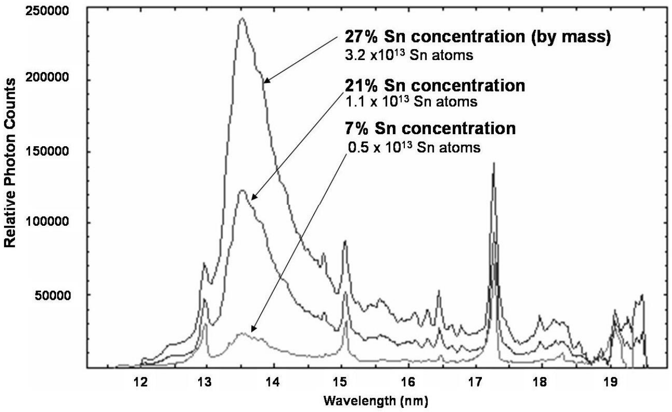

Figure 5: Spectra from tin-doped droplet target for different tin concentrations.

O'Sullivan and Faulkner have observed the effect of tin concentration on the EUV spectrum of emission from solid planar targets of tin-plastic, which are composed of metallic tin and araldite mixture[27]. The spectra from the tin-plastic targets showed significant widening in the 13.5nm UTA when the tin concentration was increased merely from 1% to 5% tin by mass. This broadening of the UTA, however, was not observed in the case of the tin-doped droplet target; the 13.5nm UTA from the droplet source remains narrow (~6.5% FWHM) for a large range of tin concentrations, from 7% to 27% tin by mass.

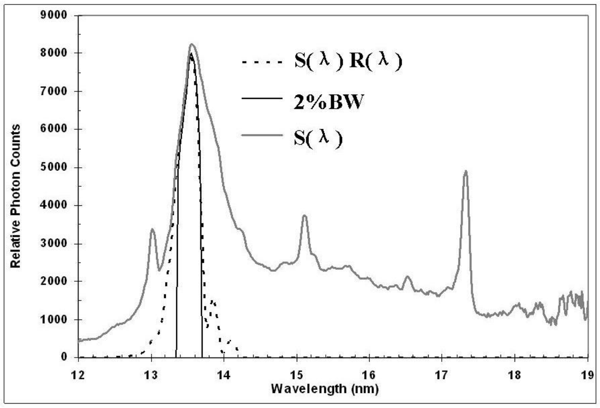

Figure 6: Convolution of spectra S(λ) with reflectivity of the Mo-Si multilayer mirror R(λ) to determine the in-band 2% BW energy from the measured energy.

The typical value of conversion efficiency of the tin-doped droplet target measured with the Flying Circus is ~1.1% (over 2π sr and within the 2%BW of the Mo-Si multilayer mirror bandwidth), where it is assumed that the emission from the source is isotropic. Measurements of conversion efficiency for solid planar tin target give typical values of 2%. The method for calculating conversion efficiency and quoting it as "% in 2%BW over 2π sr" is explained in Ref. 23. The method involves convolving the spectra of the source $S(\lambda)$ with the mirror reflectivity function $R(\lambda)$, as shown in Fig. 6, and calculating a coefficient C corresponding to the 2%BW criterion. If E_{source} is the source's energy emitted over 2π sr (assuming isotropic emission) and E_{laser} the laser pulse energy, then the conversion efficiency is equal to

$$\text{Conversion Efficiency} = C\left(\frac{E_{\text{source}}}{E_{\text{laser}}}\right)$$

4. LASER PLASMA HYDRODYNAMIC SIMULATIONS

The radiation emitted from hot, dense laser plasma depends strongly on the plasma conditions such as electron temperature and electron density, which are influenced by various laser and target parameter on plasma heating. Simulations using laser plasma codes can provide useful information about the plasma dynamics to find an optimum laser and target parameter where the useful EUV radiation is produced most efficiently. We have been employing the one-dimensional hydrodynamic simulation code MEDUSA 103 for this purpose[28]. The code allows the user to adjust various laser and target parameters: laser pulse duration, intensity, wavelength, pulse shape, target atomic mass and composition, to model the electron density, electron and ion temperature, plasma velocity, average ion charge state, as a function of time and space.

Fig. 7 shows a typical simulation result for a tin-doped target of spherical geometry (35µm diameter), showing the variation of the predicted electron temperature and electron density in space, for a time corresponding to the peak of the laser pulse. The horizontal axis is the distance measured from the center of the target. The simulation shows that by the time the laser pulse reaches this peak intensity, the absorption region of the plasma, primarily by inverse bremsstrahlung absorption, located at distances from the center of the target that are below the critical density for the laser radiation ($\sim 10^{21}$ cm^{-3}) has expanded to completely fill the laser spot size. Also, the electron temperature reaches a maximum value around that same region.

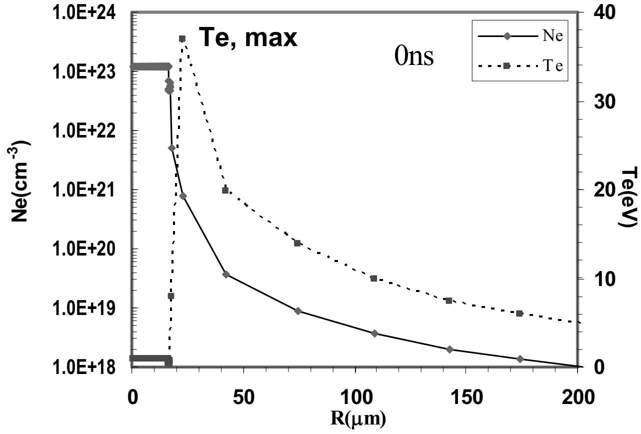

Figure 7: Typical simulation results for tin-doped droplet target, showing the electron temperature and density.

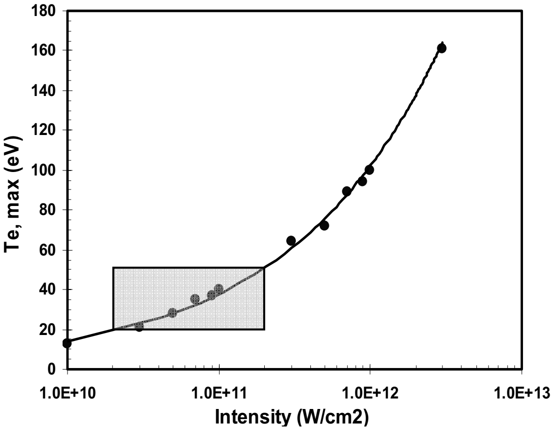

Figure 8: The maximum T_e as a function of laser intensity predicted by MEDUSA, for a particular target parameter.

A series of simulations were made to observe the dependence of the predicted maximum electron temperature as a function of laser intensity for the tin-doped droplet target laser plasma source using a particular target parameter: 35µm diameter spherical target with concentration 30% tin by mass. Results were obtained for laser intensities ranging from 1 x 10^{10} to 3 x 10^{13} W/cm^2, as shown in Fig. 8, where the dependence of $T_{e,max}$ and intensity is a rather smooth function.

From the calculated Sn ion stages distribution as a function of electron temperature[24], it was predicted that optimum production of the 13.5nm UTA from tin occurs in the range of electron temperature from ~20 - 50eV. For that range of electron temperature, the results from MEDUSA indicate that the optimum laser intensity for irradiating the target would be located within 0.2 – 2.0 x 10^{11} W/cm^2, for this particular target parameter. This predicted region for optimum emission lies within the cross hatched box. For higher concentrations of tin, the maximum electron temperature curve would shift upward, and thus it is expected that less laser intensity is required to achieve optimum emission from the target. These results provide helpful insight for the experimental work in developing an efficiency laser plasma source for EUV lithography. Future studies will involve finding the effect of laser intensity to cross check with the result from simulation.

5. CONCLUSION

The tin-doped droplet laser plasma source is being developed for use in EUV lithography. Combining the mass-limited target concept with tin as the choice of target material, the source can be made to provide sufficient power and debris-free. We have reported encouraging results from this laser plasma source. More effort will be made in spectroscopy studies to characterize the source's emission for different laser and target parameters. Results from hydrodynamic code are providing valuable information. These studies as well as future studies on the plasma dynamics will provide systematic approach to design a successful source.

ACKNOWLEDGMENTS

The authors gratefully acknowledge useful discussions with Dr. Gerard O'Sullivan from University College, Dublin; the technical support of colleagues at LPL, Dr. Greg Shimkaveg, Somsak Teerawattenasook, Rob Bernath and Joshua Duncan. This work is supported by International SEMATECH and the State of Florida.

REFERENCES

1. C. Gwyn, D.Attwood, D. Sweeney, "Extreme ultraviolet lithography,"*, J. Vac. Sci. Technol. B* **16** (6), 3142 (1998)
2. D.A. Tichenor *et al.,* "Diffraction-limited soft-x-ray projection imaging using a laser plasma source," *Opt. Lett.* **16**, 557 (1991)
3. S. Ter-Avetisyan *et al*., "Efficient extreme ultraviolet emission from xenon-cluster jet targets at high repetition rate laser illumination," *J. App. Opt.* **94**, 5489 (2003)
4. B.A.M. Hansson, L. Rymel, M. Berglund, and H.M. Hertz, "A liquid-xenon-jet laser-plasma X-ray and EUV source," *Microelectronic Eng.* **53**, 667-670 (2000)
5. H. Komori *et al*., "Laser-produced light source development for extreme ultraviolet lithography," *J. Vac. Sci. Tech. B* **21**, 2843 (2003)
6. H. Shields *et al*., "Xenon target performance characteristics for laser-produced plasma EUV sources," *Proc. SPIE,* vol. 4688, 94 (2002)
7. F. Jin, K. Gabel, M. Richardson, M. Kado, A.F. Vassiliev, and D. Salzmann, "Mass-limited laser plasma cryogenic target for 13-nm point x-ray sources for lithography," *Proc. SPIE*, vol. 2015, pp. 151-159, (1993)
8. F. Jin, M. Richardson, G. Shimkaveg, and D. Torres, "Characterization of a laser plasma water droplet EUV source," *Proc. SPIE*, vol. 2523, pp. 81-87, (July 1995)
9. M. Richardson, D. Torres, C. DePriest, F. Jin, and G. Shimkaveg, "Mass-limited, debris-free laser plasma EUV source," *Optics Comm*., **145**, pp. 109-112 (1998)
10. R.C. Constantinescu, J. Jonkers, P. Hegeman, and M. Visser, "A laser generated water plasma source for extreme-ultraviolet lithography and at wavelength interferometry," *Proc. SPIE*, vol. 4146, 101-112 (2000)
11. S. Dusterer, H. Schwoerer, W. Ziegler, C. Ziener, and R. Sauerbrey, "Optimization of EUV radiation yield from laser-produced plasma," *App. Phys. B*, **73**, 693-698 (2001)
12. U. Vogt, H. Stiel, I. Will, M. Wieland, T. Wilhein, P.V. Nickles, and W. Sandner, "Scaling-up a liquid water jet laser plasma source to high average power for Extreme Ultraviolet Lithography," *Proc. SPIE*, vol. 4343, 87-93 (2001)
13. G. Schriever, M.Richardson and E.Turcu, (submitted for publication)

14. R.C. Spitzer, T.J. Orzechowski, D.W. Phillion, R.L. Kauffman, and C. Cerjan, "Conversion efficiencies from laser-produced-plasma in the extreme ultraviolet regime," *J. Appl. Phys*., vol. 79, pp. 2251-2253 (1996)
15. G. O'Sullivan and P. Dunne, "Spectroscopy of a 13.5nm laser plasma source," presentation at International SEMATECH EUVL Source Workshop, Oct 2002, Dallas, TX
16. M.A. Klosner, and W.T. Silfvast, "Intense xenon capillary discharge extreme-ultraviolet source in the 10–16-nm-wavelength region," *Opt. Lett*., **23**, 1609 (1998)
17. N. Bowering, M. Martins, W.N. Partlo, I.V. Fomenkov, "Extreme ultraviolet emission spectra of highly ionized xenon and their comparison with model calculations," J. App. Phys., **95**, 17 (2004)
18. First mentioned in a report by JMAR Research Corp.at the EUVL Source Workshop , March 2, 2001, Santa Clara, CA
19. C-S. Koay, *et al*., "High conversion efficiency tin material laser plasma source for EUVL", *Proc. SPIE,* vol. 5037, pp. 801-806 (2003)
20. K. Takenoshita, C-S. Koay, M. Richardson, I.C.E. Turcu, "The Repeller Field debris mitigation approach for EUV sources", *Proc. SPIE*, vol. 5037, pp. 792-800 (2003)
21. JMAR laser, diode-pumped 5000W, 100kHz or TRW laser, diode-pumped Nd:YAG, 4500W, 5kHz
22. K. Takenoshita, C. Koay, S. Teerawattanasook, M. Richardson, "Debris studies for the tin-based droplet laser-plasma EUV source," *Proc. SPIE*, vol. 5374 (2004)
23. M. Richardson, "Laser plasma EUVL sources: progress and challenges," *Proc. SPIE*, vol. 5374 (2004)
24. W. Schwanda, K. Eidmann, and M.C. Richardson, "Characterization of a flat-field grazing-incidence XUV spectrometer," *J. X-ray Sci. and Tech*., vol. 4, pp. 8-17 (1993)
25. X-ray CCD camera model: PI-SX:512 from Princeton Instrument
26. R. Stuik, F. Scholze, J. Tummler, and F. Bijkerk, "Absolute calibration of a multilayer-based XUV diagnostic," *Nuclear Inst. Method Phys. Res. A*, **429**, 305-316 (2002)
27. G. O'Sullivan and R. Faulkner, "Tunable narrowband soft x-ray source for projection lithography," *Opt. Eng*., vol. 33, pp. 3978-3983 (1994)
28. P.A. Rodgers, A.M. Rogoyski, and S. J. Rose, *MED101: a laser-plasma simulation code.* User guide (Appleton, Rutherford, N.J., 1989)