LPP Source System Development for HVM

David C. Brandt*, Igor V. Fomenkov, Alex I. Ershov, William N. Partlo, David W. Myers
Norbert R. Böwering, Nigel R. Farrar, Georgiy O. Vaschenko, Oleh V. Khodykin, Alexander N. Bykanov
Jerzy R. Hoffman, Christopher P. Chrobak, Shailendra N. Srivastava, Imtiaz Ahmad, Chirag Rajyaguru
Daniel J. Golich, David A. Vidusek, Silvia De Dea, Richard R. Hou

Cymer Inc., 17075 Thornmint Court, San Diego, CA 92127, USA

ABSTRACT

Laser produced plasma (LPP) systems have been developed as a viable approach for the EUV scanner light source for optical imaging of circuit features at sub-32nm and beyond nodes on the ITRS roadmap. This paper provides a review of development progress and productization status for LPP extreme-ultra-violet (EUV) sources with performance goals targeted to meet specific requirements from leading scanner manufacturers. We present the latest results on power generation, stable and efficient collection, and clean transmission of EUV light through the intermediate focus. We report on measurements taken using a 5sr collector optic on a production system. Power transmitted to intermediate focus (IF) is shown. The lifetime of the collector mirror is a critical parameter in the development of extreme ultra-violet LPP lithography sources. Deposition of target material as well as sputtering of the multilayer coating or implantation of incident particles can reduce the reflectivity of the mirror coating during exposure. Debris mitigation techniques are used to inhibit damage from occuring, the results of these techniques are shown. We also report on the fabrication of 5sr collectors and MLM coating reflectivity, and on Sn droplet generators with droplet size down to 30μm diameter.
Keywords: EUV source, EUV lithography, Laser Produced Plasma, Normal Incidence Collector

1. INTRODUCTION

EUV Lithography is the front runner for next generation critical dimension imaging after 193 nm immersion lithography for layer patterning below the 32 nm node; beginning in 2013 according to the International Technology Roadmap for Semiconductors (ITRS). NAND Flash devices are expected to have the need for this manufacturing technology as soon as 2011, with pilot line system introduction required as early as 2010. The availability of high power 13.5 nm sources has been categorized as high risk and ranked as critical with other technologies requiring significant developments to enable the realization of EUV lithography. High sensitivity photoresists with good line-edge-roughness (LER) and line-width-roughness (LWR) are needed to keep the required source power within reasonable limits. Photoresist sensitivity and other light absorbing elements are the basis to derive EUV source power requirements within the usable bandwidth (BW) of 2 %. According to the joint requirements from scanner manufacturers an EUV power of > 115 W 2 % BW at the intermediate focus (IF) is required for 5 mJ/cm^2 photoresist speed to enable > 100 wph scanner throughput, and 180 W 2 % BW at IF is needed for 10 mJ/cm^2. Photoresist sensitivities above 20 mJ/cm^2 could drive power requirements well above the 200 W level, and the need for a spectral purity filter (SPF) could increase the requirements even higher. A scalable EUV source architecture is needed to enable the evolution of EUV lithography during the life cycle of the technology. Laser-produced-plasma (LPP) sources are expected to deliver the necessary high power for critical-dimension high-volume manufacturing (HVM) scanners for the production of integrated circuits in the post-193 nm immersion era.[1]

LPP EUV lithography light sources generate the required 13.5 nm radiation by depositing laser energy at 10.6 micron wavelength into tin (Sn) creating a highly ionized plasma with electron temperatures of several 10's of eV. EUV photons are radiated by these ions into all directions. The light is collected with a normal-incidence mirror (collector), and focused to an intermediate point from where it is relayed to the scanner optics and ultimately to the wafer. The conversion efficiency (CE) of the laser energy into EUV energy is critical to meeting the required power levels.

David C. Brandt, dbrandt@cymer.com

Alternative Lithographic Technologies, edited by Frank M. Schellenberg, Bruno M. La Fontaine
Proc. of SPIE Vol. 7271, 727103 · © 2009 SPIE · CCC code: 0277-786X/09/$18 · doi: 10.1117/12.814228

A prototype configuration based on this approach is described and several recent developments are discussed. The normal-incidence mirror is protected from the plasma by advanced debris mitigation technology. High-energy ions, fast neutrals, and residual source element particles are mitigated to maintain the reflectivity of the collector mirror and enable a long lifetime of this component. Metrologies to measure the properties of emitted light at both the plasma and IF are used to qualify the performance of the source.[2]

2. EUV LPP SYSTEM

Our research and development system, described previously[1, 3-5] and shown in Figure 1, serves as the primary tool to test the fundamental capability and longevity of production designs. The performance is monitored by metrology directed at both plasma and at intermediate focus positions. A multi-location witness sample holder at the position of the collector is used to acquire life test data on various MLM samples allowing the effectivity of the debris mitigation and reflectivity of the MLM coatings to be evaluated quantitatively. Alternatively, a sub-aperture collector mirror with 1.6 sr collection angle can be installed. Integrated controls permit semi-automatic operation of the system as well as monitoring and data collection from the various metrology instruments attached to the LPP chamber.

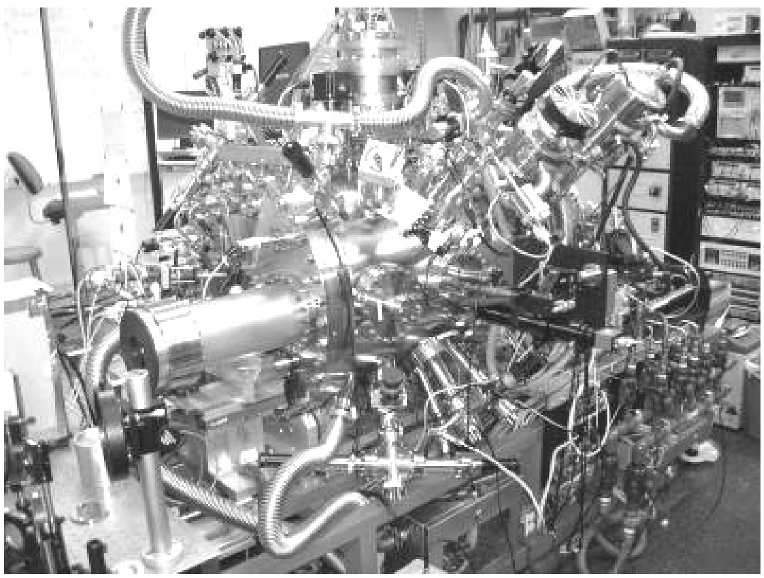


Figure 1: Photograph of the research and development system (LT1) currently in use.

Two manufacturing bays for production of prototype and pilot LPP sources with class 10,000 clean-room space were completed in 2008. Following installation and extensive testing of the drive laser system and other major system components several source systems are being assembled; the first production system for shipment to a customer is fully integrated with its collector and debris mitigation subsystems. The water-cooled chamber of the production systems is larger in diameter compared to the development system in order to house a 5 sr collector. The optical elements are also water-cooled to enable high-power operation. Other system components like laser beam transport, support frame, vacuum pumping, droplet generation, controls and monitoring were also significantly expanded and improved to meet production requirements. A photograph of a production system in its manufacturing bay is shown in Figure 2.

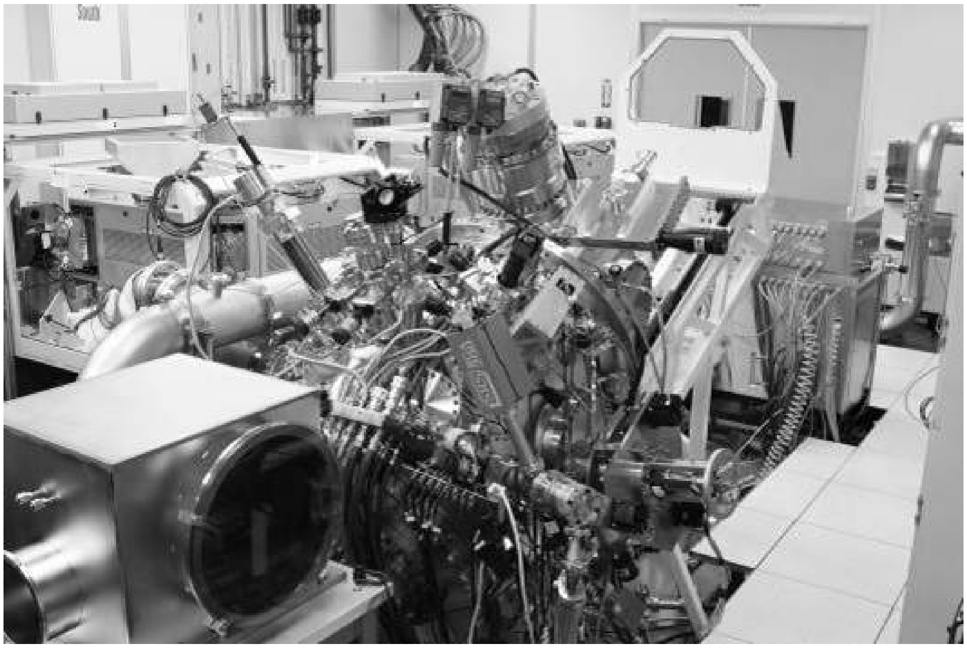


Figure 2: Photograph of a production LPP system.

3. RECENT DEVELOPMENT RESULTS

Initially, firing patterns of 1ms burst duration and 8% duty cycle were used to demonstrate 100W EUV power output. This allowed the Conversion Efficiency (CE) of the laser and fuel combination to be validated; using 10.6μm radiation and Sn droplets as the target material a CE of 3.0% was measured at this duty cycle[6]. The firing pattern has recently been extended to 400ms bursts and 80% duty cycle, as shown in Figure 3, which is typical of scanner operating conditions.

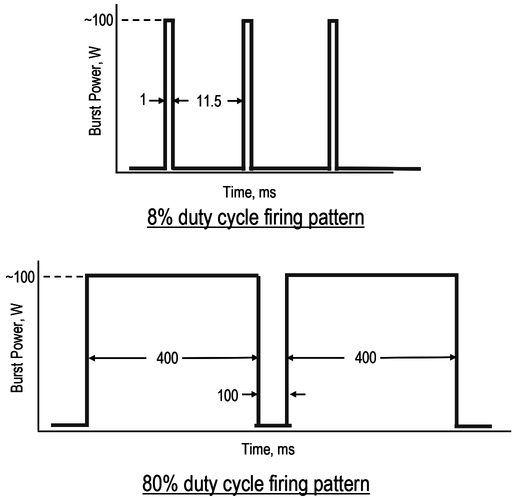


Figure 3: Burst pattern for low and high duty cycle operation.

Figure 4 shows the power of a production system running at 80% duty cycle, as determined from measurements at plasma. IF-equivalent average powers above 20W were reached using standard assumptions of 50% reflectivity for 5 sr collector and 90% optical transmission. Initially, time limitations for extended operation at high duty cycles were on the order of several seconds. Thermal lenses may appear in the optics if not actively and properly water cooled. Thermal limitations were overcome, and the system was ramped up with successively longer duration operation to hours of continuous uptime. Extended operation of the EUV source for 18 hours was successfully demonstrated. Figure 4 shows the continuous average EUV power of 20 W (IF equivalent) sustained over the extended operational hours. The new production systems are capable of high-duty cycle operation for prolonged time periods and are presently being optimized for high-power operation at 80% duty cycle, with ultimate target of 100%.

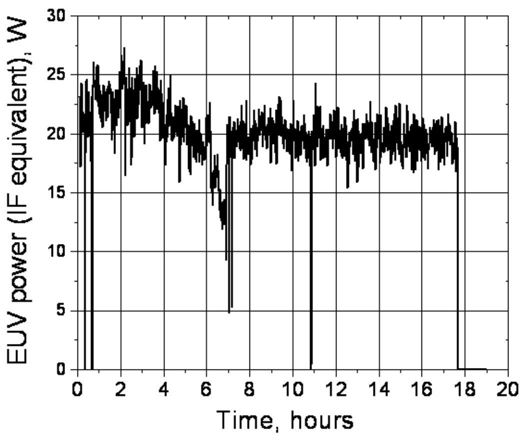


Figure 4: IF equivalent average EUV power vs. time. The source was operated at 50 kHz, 80% duty cycle, with 400ms burst duration.

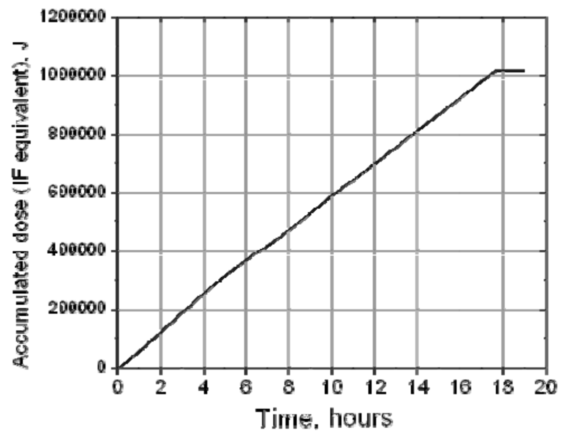


Figure 5: Dose accumulation, exceeding 1MJ during 18 hours of operation at 80% duty cycle and 400ms burst duration.

Long-term high-power source operation is required to support high wafer throughput at the exposure tool. Figure 5 shows the total accumulated EUV dose at IF determined from the measured EUV power at plasma using standard assumptions during 18 hours of run time. In this period, more than 1 MJ of accumulated dose was reached with the light source operation. Such a dose level corresponds to the exposure of a batch of approximately 250 wafers of 300 mm size. Further EUV power increase is planned to reach dose delivery levels of several MJ per day.

A key challenge is to maintain the high collection efficiency and stable power output over long periods of time in order to meet Cost of Ownership targets. The proximity of the collector optic to the high temperature plasma exposes it to high energy ions, neutral atoms and other debris which can potentially damage the coating and reduce reflectivity. The three main degradation mechanisms are deposition of tin particle debris from the droplets, erosion of the mirror by high energy ions and neutral atoms and deposition of tin vapor. The decrease of the droplet size has arguably the most important beneficial impact on the effectiveness of debris mitigation techniques. It is necessary to reduce the load on the individual debris mitigation subsystems responsible for eliminating each degradation mechanism. Droplet sizes with diameters as small as 30µm have been demonstrated for extended run times and are now routinely used in LPP systems for integrated testing. Such small droplets provide the added advantage of reducing the annual tin consumption, which also minimizes tin material costs.

One debris mitigation subsystem addresses multilayer erosion by significantly reducing the ion flux incident at the mirror surface by up to four orders of magnitude, and the ion energy by about an order of magnitude. Erosion can also be addressed by adding sacrificial multilayers during the coating step of collector fabrication. A second debris mitigation subsystem eliminates tin deposition, which is critical because a deposited tin layer with a thickness of only about 1nm results already in unacceptable reflectivity reduction by absorption of the EUV radiation. The debris mitigation technology was initially developed and validated on the LT1 system using both witness samples and sub-aperture 1.6sr collectors. In October of 2008 the effectivity of the debris mitigation was demonstrated in continuous operation over an eight hour period. The data was collected at EUV powers of 45W with 8% duty cycle by using 1 ms long laser bursts on 50µm diameter droplets[7,8]. Figure 6 shows a new example of effective debris mitigation technology. The recorded EUV power measured over fifty one hours at 25% duty cycle was ~40W at IF, as shown in Figure 7.

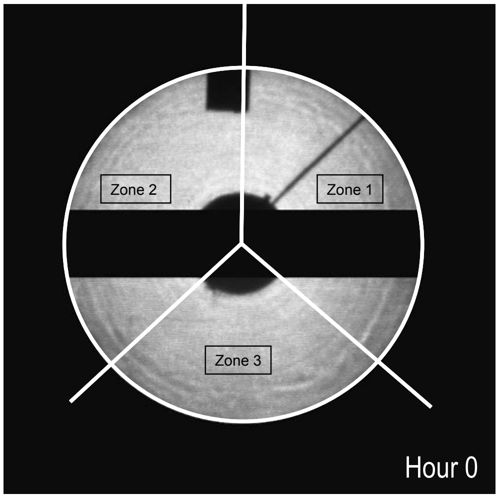


Figure 6: Far field EUV intensity distribution of 1.6sr collector.

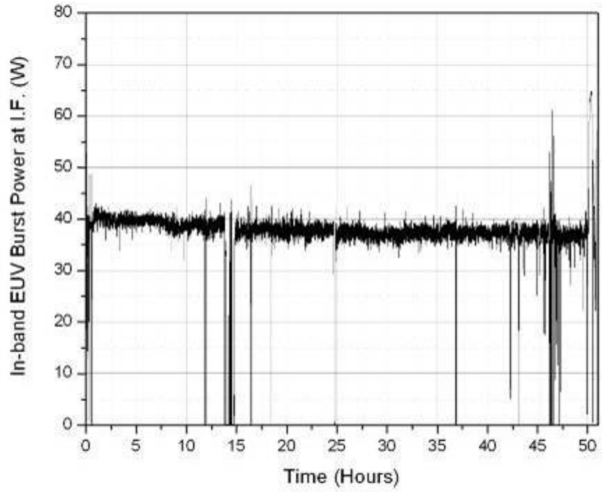


Figure 7: IF equivalent EUV power of 40W and 25% duty cycle during 51 hours of exposure of 1.6sr collector.

Zones 1, 2, and 3 were configured with different geometries of protection to accelerate the testing. Zone 1 and 2 showed some degradation early in the test and continued to reduce in reflectivity during the remaining hours. At the end of 40 hours of testing Zone 3 continued to reflect EUV as efficiently as in the beginning of the test. However, after 40 hours of exposure Zone 3 began to degrade as is shown in the 50 hours exposure image in Figure 8. It is believed that this was in part influenced by encroachment from Zones 1 and 2. Figure 9 shows the relative reflectivity of a 3cm x 3cm area of Zone 3 as viewed from IF with a Zr coated fluorescence converter and compared to an EUV monitor measuring EUV power at plasma. The relative reflectivity stays nearly constant for the first 40 hours and then begins to decline. Zone 3 geometries were ultimately determined to be successful and were transferred to our production system design. More information on this testing is available in a more detailed description in a companion paper (7271-119) in these proceedings[6].

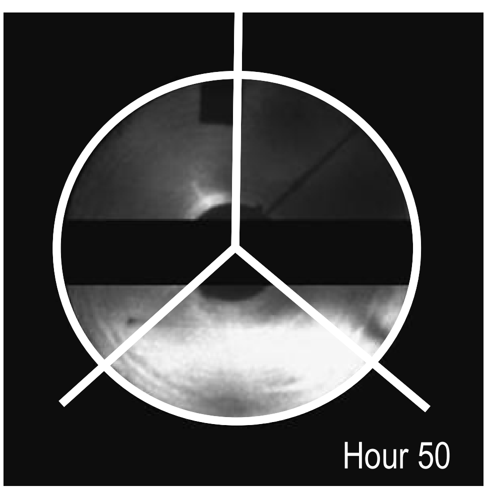


Figure 8: Far field of EUV intensity distribution of 1.6sr collector after 50 hours of exposure.

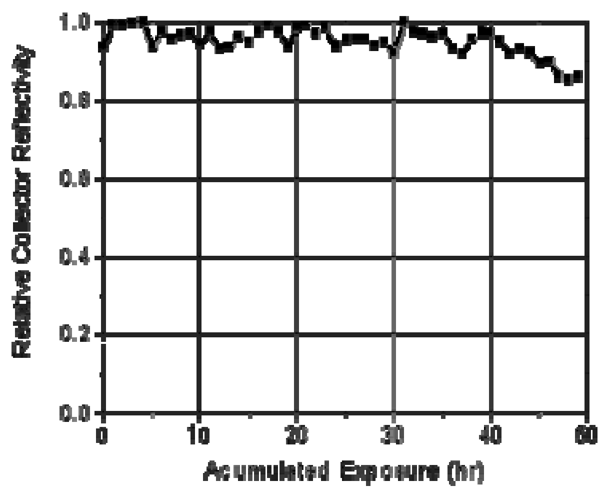


Figure 9: Relative reflectivity of Zone 3 determined from IF data in relation to the EUV power monitor data at plasma.

Figure 10 shows the first results for a fully integrated production EUV source system with 5sr collector mirror. The far-field intensity distribution is shown as recorded with a Zr-coated fluorescence converter and CCD camera. Non-uniform structures in the image observed during the first tests can be attributed to deficiencies of the collector substrate. The prototype system was operated with bursts of 400 ms duration at 40% duty cycle. Figure 11 shows the corresponding measured 45W to 50W average EUV power level under these conditions.

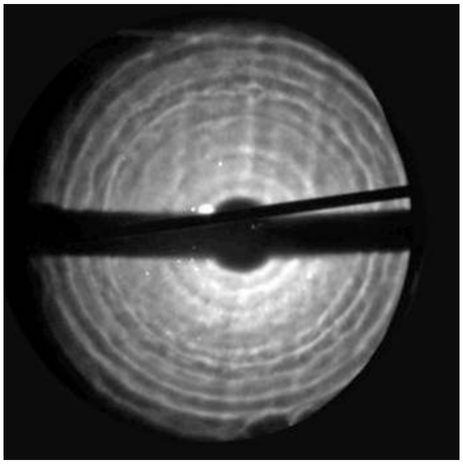


Figure 10: Far field EUV intensity distribution of 5sr collector.

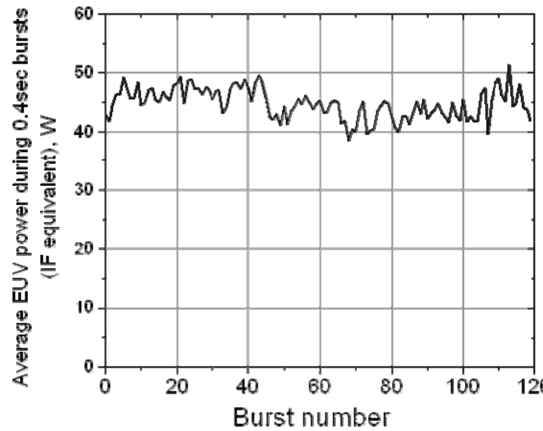
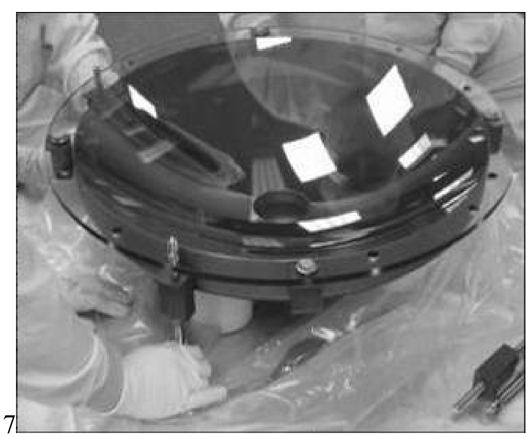


Figure 11: EUV power measured during 120 bursts of 400ms duration.

4. NORMAL INCIDENCE COLLECTORS

Cymer's LPP EUV source employs near-normal-incidence mirrors with a very large solid angle for light collection. Such a geometry has numerous advantages, which have been discussed elsewhere.[1,9,10] As we reported earlier[1,8], the complete infrastructure is in place for manufacturing of large-size normal-incidence collector mirrors. For demonstration of the light collection capabilities of our source several 1.6 sr sub-aperture versions (300 mm optical diameter) have been produced and are currently used in the development system for testing. Large substrates (> 650 mm diameter) of the full HVM design with 5sr collection angle are now completed or at the final stages of polishing reaching surface roughness levels below 0.2 nm. The substrates have also been coated with graded multilayer coatings with layer periods optimized for high EUV reflectance at the corresponding incidence angles.



7

Figure 12: 5sr normal incidence collector mirror after multi-layer coating. A protection cover is used during transport and handling.

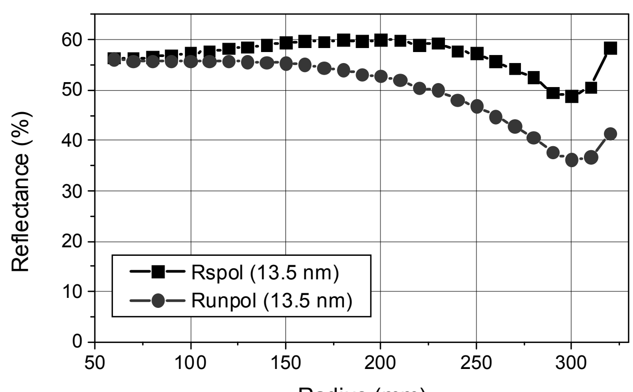


Figure 13: Squares: Reflectivity of the 5sr collector as measured with s-polarized EUV light of 13.5nm at PTB. Dots: Corresponding data determined for unpolarized light.

Figure 12 shows a picture of a large collector substrate with protection cover in its shipping frame. Figure 13 displays the EUV reflectance at 13.5 nm wavelength obtained as a function of radial position on a mirror with s-polarized synchrotron radiation. Also shown are the corresponding reflectance values for incidence of unpolarized light as derived from results obtained with test samples at different radial positions. When taking into account the contributing reflecting area, the reflectance for unpolarized light at 13.5 nm corresponds to an average value of 47.0 %.

5. DROPLET GENERATOR

The droplet generator provides a constant stream of liquid tin targets (droplets) to the focal point of the collector where the CO_2 laser pulse is used to create the light-emitting plasma. The main requirement for the generators is to produce reproducibly small droplet targets of identical size at the repetition rate of the laser pulses (typically 50 kHz).[11] Droplets with high temporal and spatial stability have been consistently produced over hundreds of hours of operation time, with the duration mainly limited by the capacity of the tin reservoir vessel. The longest continuous run of the droplet generator achieved so far is in excess of 500 hours. Figure 14 shows the position stability of 50 µm diameter droplets when the stream is propagating in a vertical direction and Figure 15 displays the corresponding result for horizontal operation. Short-term position stability is better than 1 µm in both cases. The slow position drift observed in Figs. 14 and 15 (7 µm/min and 15 µm/min, respectively) can be compensated by the active position control system as was demonstrated separately.

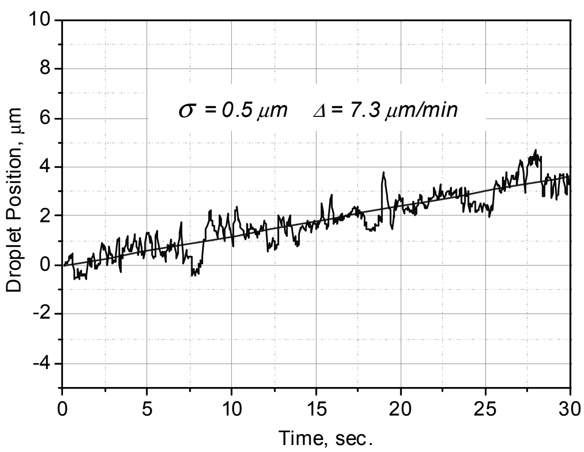


Figure 14: Vertical position stability of 50 µm droplets.

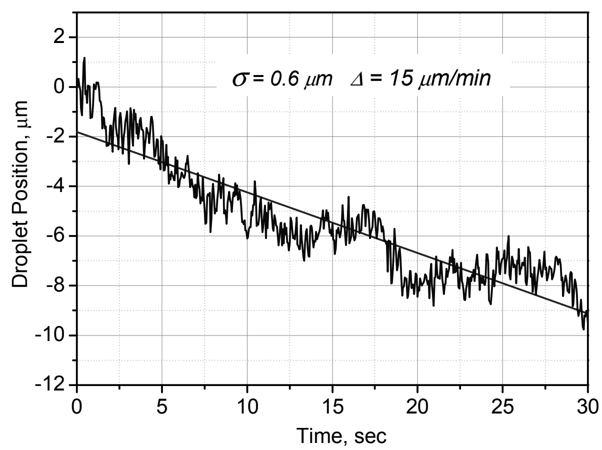


Figure 15: Horizontal position stability of 50 µm droplets.

We have also developed the technology for generating droplets with diameter of ~30 µm. These droplets meet the stability and timing requirements for the present system, as was tested during 200 hours of operation without failure. Droplet size reduction leads to a significant efficiency increase for debris mitigation technologies. Second generation sources should have droplet diameters further reduced to ~10 µm. When droplets of this size are generated at a frequency of 50 kHz, about 1 liter of tin is consumed per year.

6. ELECTRICITY CONSUMPTION

A major utility for the EUV source is the electrical power that the system requires. Up to now, the cost has been perceived as prohibitive, yet recent *actual* measurements on the EUV source indicate that power requirements may have been overestimated in the past[12]. With the operation of the EUV source at nominal scanner operating conditions, for the first time we can estimate with reasonable certainty the amount and cost of electrical power used. These calculations are shown in Table 1. The roadmap for additional EUV power actually predicts a decreasing cost of electrical consumption. Despite higher throughput tools and greater EUV power, this decreased cost is obtained by the more efficient utilization of the available EUV light. A reduced percentage of source on-time is required for the exposure (greater scanner overhead time), resulting in a lower usage of electrical consumption and a lower cost by as much as 10% less over the three generations depicted. It should be noted that the cost of electricity consumption used here was based on 0.07 $/kWhr. This is the estimated commercial cost published by the Energy Information Administration in November 2008 (Official Energy Statistics of US Government). Regional variability in commercial electrical costs may increase this cost to 0.10 $/kWhr. Compared to a 193nm immersion light source such as the XLR 500 with a power consumption of 112kVA the LPP EUV source consumption is approximately three times greater.

	HVM I	HVM II	HVM III
Power Consumption – Total Source Module (kW)	353	322	300
Availability / Utilization (Fully Utilized when Available)	85% / 100%	85% / 100%	85% / 100%
Source Operation Time (Percentage of Scanner Op Time)	75%	60%	49%
Electricity Cost* ($/kWhr)	0.07	0.07	0.07
Cost ($/yr)	$216k	$197k	$184k

Table 1: Estimated usage and cost of electrical power

7. ROADMAP

Currently, our prototype source is undergoing acceptance testing. HVM I source designs will be based on the learning obtained from prototype sources. The LPP source roadmap is shown in Table 2. The pilot product is expected to meet requirements for pre-production or beta generation scanners in 2009 with in-band EUV output powers of >100 W using a 11 kW CO_2 laser system on Sn droplets with 3.0 % CE. The normal-incidence collectors used will have ~ 5 sr of light collection angle with multilayer coatings with EUV reflectivities > 60 % on average over the surface. Transmission losses due to absorption and debris mitigation techniques are projected to be less than 20 %. It is expected that requirements for later generation LPP EUV sources will drive source powers above the 200 W level (HVM II, HVM III) with CO_2 laser technology delivering >20 kW of power. Improvements in CE and collection efficiency should provide additional gain to counter losses due to transmission and obscurations so that power levels exceeding 400 W at IF can be reached.

EUV Source Power Roadmap			
	HVM I	HVM II	HVM III
Drive laser power (kW)	**11**	**19**	**>20**
In-band CE (%)	3.0	3.5	4.0
Collection Efficiency (sr)	5	5.2	5.5
Collector Reflectivity (%)	>60	>60	>60
Optical Transmission (%)	80	85	90
Total EUV power at IF (W)	**>100**	**>200**	**>400**

Table 2: Projected LPP EUV source roadmap

8. SUMMARY

Laser-produced plasma has been shown to be the leading source technology with scalability to meet requirements from leading scanner manufacturers and provide a path toward higher power as the lithography tools evolve over their life cycle. EUV power exceeding 20W at intermediate focus and run times up to 18 hours of stable source operation at 80%

duty cycle and 400ms burst lengths has been reported with accumulated dose exceeding 1 MJ. Using a sub-aperture collector mirror, the far-field image of the EUV distribution and collector reflectivity behind IF was recorded, showing good protection in zone 3 over 51 hours of operation. Normal-incidence collector mirrors of diameter > 650mm and > 5 sr light collection are produced and integrated into production LPP systems. LPP EUV source system manufacturing has progressed well. The high-conversion-efficiency combination of 10.6 µm laser radiation and Sn source element has been demonstrated with CE in excess of 3 %. The high CE values in our roadmap allow high EUV power at relativity low laser power to enable low cost of operation. EUV lithography is expected to be the critical dimension imaging solution in the post-193 nm immersion era. LPP source technology with power levels exceeding 400W is expected to enable the IF power requirement projected in the future, and to provide the much needed margin for photoresist sensitivity, spectral purity filters, optics degradation, process latitude, and overall equipment throughput. Cymer plans the commercialization of EUV light sources in 2009. The company continues to meet its EUV source development commitments to industry and customers.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the valuable contributions from Martin J. Neumann and David N. Ruzic of University of Illinois, Urbana Champaign, Marco Perske, Hagen Pauer, Mark Schürmann, Sergiy Yulin, Torsten Feigl and Norbert Kaiser of Fraunhofer Institut f. Angewandte Optik und Feinmechanik, Eric Gullikson and Farhad Salmassi of Lawrence Berkeley National Laboratory, Frank Scholze, Christian Laubis, Christian Buchholz and coworkers at PTB, and Mark Tillack and Yezheng Tao of the University of California at San Diego. We are also very thankful for the invaluable support and contributions, past and present, of many scientists, engineers and technicians involved in the EUV technology program at Cymer.

REFERENCES

[1] I. V. Fomenkov, D. C. Brandt, A. N. Bykanov, A. I. Ershov, W. N. Partlo, D. W. Myers, N. R. Böwering, G. O. Vaschenko, O. V. Khodykin, J. R. Hoffman, E. Vargas L., R. D. Simmons, J. A. Chavez, C. P. Chrobak, in: *Proc. of SPIE Vol. **6517**, Emerging Lithographic Technologies XI,* M. J. Lercel, ED., 65173J, (2007).

[2] N. R. Böwering, J. R. Hoffman, O. V. Khodykin, C. L. Rettig, B. A. M. Hansson, A. I. Ershov, I. V. Fomenkov, in: *Proc. SPIE **Vol. 5752**, Metrology, Inspection, and Process Control for Microlithograpy XIX,* R. M. Silver, Ed., 1248-1256 (2005).

[3] B. A. M. Hansson, I. V. Fomenkov, N. R. Böwering, A. I. Ershov, W. N. Partlo, D. W. Myers, O. V. Khodykin, A. N. Bykanov, C. L. Rettig, J. R. Hoffman, E. Vargas L., R. D. Simmons, J. A. Chavez, W. F. Marx, D. C. Brandt, in: *Proc. of SPIE Vol. **6151**, Emerging Lithographic Technologies X,* M. J. Lercel, Ed., 61510R, (2006).

[4] B. A. M. Hansson, I. V. Fomenkov, N. R. Böwering, A. I. Ershov, W. N. Partlo, D. W. Myers, O. V. Khodykin, A. N. Bykanov, C. L. Rettig, J. R. Hoffman, E. Vargas L., R. D. Simmons, J. A. Chavez, W. F. Marx, D. C. Brandt, in: *Proc. of SPIE Vol. **5751**, Emerging Lithographic Technologies IX*, R. S. Mackay, Ed., 248-259 (2005).

[5] I. V. Fomenkov, B. A.M. Hansson, N. R. Böwering, A. I. Ershov, W. N. Partlo, V. B. Fleurov, O. V. Khodykin, A. Bykanov, C. L.Rettig, J. R. Hoffman, E. Vargas L., J. A. Chavez, W. F. Marx, D. C. Brandt, in: *Proc. of SPIE Vol. **6151**, Emerging Lithographic Technologies X,* M. J. Lercel, Ed., 61513X, (2006).

[6] I. V. Fomenkov, A. I. Ershov, W. N. Partlo, D. W. Myers, N. R. Böwering, G. O. Vaschenko, O. V. Khodykin, A. N. Bykanov, J. R. Hoffmann, C. P. Chrobak, S. N. Srivastava, D. A. Vidusek, S. De Dea, R. R. Huo, D. C. Brandt, in: *these Proc. of SPIE Vol. **7271**, Alternative Lithographic Technologies,* F. M. Schellenberg, (2009).

[7] D. C. Brandt, I. V. Fomenkov,, A. I. Ershov, W. N. Partlo, D. W. Myers, N. R. Böwering, G. O. Vaschenko, O. V. Khodykin, A. N. Bykanov, J. R. Hoffmann, C. P. Chrobak, S. N. Srivastava, D. A. Vidusek, S. De Dea, R. R. Huo, contribution at 2008 International Symposium on Extreme Ultraviolet Lithography, Sept. 28 - Oct 1 2008, Lake Tahoe CA.

[8] D. C. Brandt, I. V. Fomenkov,, A. I. Ershov, W. N. Partlo, D. W. Myers, N. R. Böwering, G. O. Vaschenko, O. V. Khodykin, A. N. Bykanov, J. R. Hoffmann, C. P. Chrobak, S. N. Srivastava, D. A. Vidusek, S. De Dea, R. R. Huo "Laser-produced plasma source system development" in: *Lithography Asia 2008, Proc. SPIE Vol. **7140**,* 71401E, (2008).

[9] T. Feigl, S. Yulin, N. Benoit, N. Kaiser, N. R. Böwering, A. I. Ershov, O. V. Khodykin, J. W. Viatella, K. A. Bruzzone, I. V. Fomenkov, D. W. Myers, in: *Proc. of SPIE Vol. **6151**, Emerging Lithographic Technologies X,* M. J. Lercel, Ed., 61514A, (2006).

[10] N. R. Böwering, A. I. Ershov, W. F. Marx, O. V. Khodykin, B. A. M. Hansson, E. Vargas, J. A. Chavez, I. V. Fomenkov, D. W. Myers, D. C. Brandt, in: *Proc. of SPIE Vol. **6151**, Emerging Lithographic Technologies X,* M. J. Lercel, Ed., 61513R, (2006).

[11] J. M. Algots, O. Hemberg, A. Bykanov, in: *Proc. of SPIE Vol. **5751**, Emerging Lithographic Technologies IX*, R. S. Mackay, Ed., 248-259 (2005).

[12] A. J. Hazelton, A. Wuest, G. Hughes, L. C. Litt, F. Goodwin, “Cost of ownership for future lithography technologies”, in: *Lithography Asia 2008, Proc. of SPIE Vol. **7140**,* 71401Q, (2008).