Liquid-Xenon-Jet Laser-Plasma Source for EUV Lithography

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ABSTRACT

The liquid-xenon-jet laser-plasma source is one of the extreme-ultraviolet (EUV) source technologies under development for EUV lithography. This paper discuss the basic, demanding, requirements of a source for EUV lithography including high in-band EUV power, absence of mirror contamination and high stability. It is further discussed how the liquid-xenon-jet can meet these requirements, and specifically how the ability to operate the plasma far from any mechanical details such as the nozzle will facilitate high power operation with low resulting mirror degradation. Furthermore, a new laser-to-EUV conversion efficiency result of 0.55 %/(2%BW 2πsr) at λ=13.45 nm is presented together with a detailed description of the method for calibrated EUV-power measurement.

Keywords: EUV lithography, laser-produced plasma, liquid jet, xenon

1. INTRODUCTION

Extreme-ultraviolet (EUV) lithography[1] at $\lambda\sim$13.5 nm is currently one of the strongest candidates to succeed deep-ultraviolet lithography for large-scale manufacturing.[2] One of the main obstacles towards the realization of EUV lithography is that no source of EUV radiation is currently available meeting all the specifications for a commercial tool. Several source concepts are, however, under development,[3] all based on hot plasmas. These include electrically driven plasmas such as, z-pinch, plasma focus, capillary discharge and hollow cathode discharge, as well as several laser-produced-plasma concepts.

In this paper we report on the current status of the xenon liquid-jet laser-plasma EUV source.[4,5] This specific source combines the advantages of the microscopic-liquid-jet target method[6,7] and an inert-gas, high-Z target material. These advantages will be further discussed in the paper, including how the ability to operate the plasma far from any mechanical parts makes it possible for this source to address the high power loads associated with high EUV power generation. New results regarding the conversion efficiency (CE) from laser to in-band EUV will also be presented, but first some of the main requirements of a source for EUV lithography will be reviewed.

2. REQUIREMENTS OF A SOURCE FOR EUV LITHOGRAPHY

The two most important requirements of a source for EUV lithography are, first, to produce enough in-band EUV power so that some collector optics can deliver the necessary power to the illumination optics and, second, doing this without damaging the collector optics. The exact amount of power that is needed for a production tool is not known at the moment since it depends on many factors such as mirror reflectivity, number of mirrors and resist sensitivity. However, the different manufacturers of lithography tools have stated that 50-150 W in a 2% bandwidth around $\sim$13.5 nm have to be collected by the condenser.[8]

All source concepts under consideration today for EUV lithography are based on hot plasmas. The plasma material and the way the plasma is created, electrically or laser driven, differs however. On the other hand, all concepts have in common that the conversion efficiency (CE) from drive power to in-band EUV is rather poor, at the best in the 1–2% range. Therefore, one of the main problems of all source concepts is that the high drive power needed to create the plasma will result in severe thermal problems. The only ways to decrease the needed drive power, if the requirement of needed in-band EUV power cannot be relaxed by for example increased resist sensitivity,

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CE [%/(2%BW 2πsr)]	condenser solid angle [sr]		
	1.8	π	2π
0.5	**70 kW**	**40 kW**	**20 kW**
1.0	**35 kW**	**20 kW**	**10 kW**
1.5	**23 kW**	**13 kW**	**7 kW**

Table 1. The drive power needed to create 100 W of collectable in-band EUV power, depending on the conversion efficiency (CE) and the solid angle captured by the condenser.

is to increase the CE or the collection efficiency (solid angle and reflectivity). Table 1 gives an idea of how the drive power needed is influenced by the CE and the collection solid angle, assuming that 100 W of in-band EUV needs to radiate into the condenser's solid angle. Two conclusions can be drawn from the table, first that increasing the collection angle and the CE does improve the situation, but second that although the situation is improved, still a lot of drive power will be needed. Next section will describe the liquid-xenon-jet laser-plasma concept and comment on how it deals with the requirements stated here, and also the requirement of high emission stability for good dose control.

3. THE LIQUID-XENON-JET LASER-PLASMA SOURCE

The principle for laser-plasma EUV generation utilizing a liquid-xenon jet as target is shown in Fig. 1. The liquid-

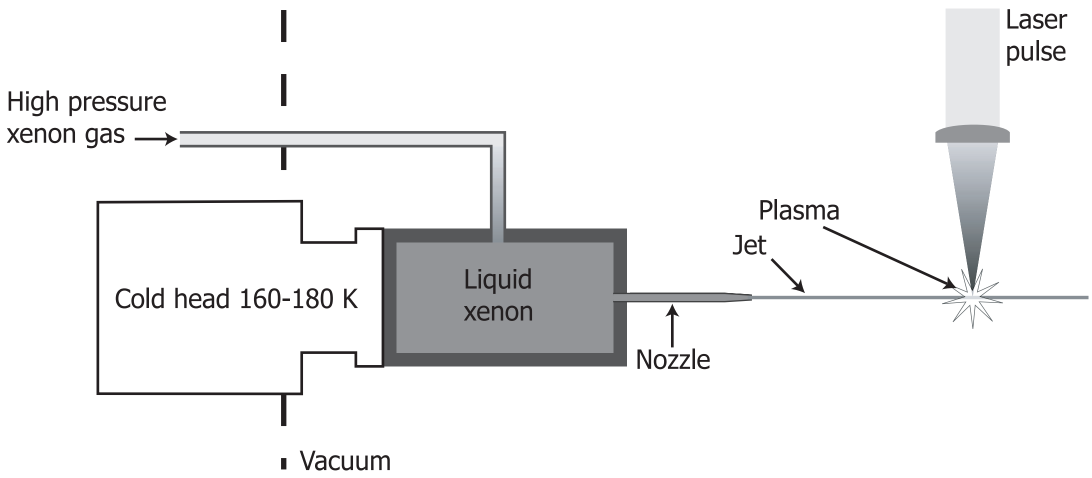

Figure 1. The principle for laser-plasma EUV generation utilizing a liquid-xenon jet as target.

xenon jet is formed by forcing xenon gas under high pressure into a small reservoir cooled to the condensation temperature of xenon. A thin glass capillary nozzle with an orifice of around 10 μm in diameter is attached to the reservoir, producing a microscopic jet of liquid xenon into a vacuum chamber. The plasma is generated by focusing a short laser pulse onto the jet. The laser used in the experiments described below is a Nd:YAG laser delivering up to 300 mJ, ~5 ns long pulses at λ=1064 nm. The beam is focused onto the xenon jet with a 50 mm lens.

To discuss the properties of this source concept one can start by recalling how it was found in last section that the main routes to minimizing the need for very high driving power was to increase the conversion efficiency and the collection angle. Xenon is a high-Z target promising high CE,[9] and indeed, as will be discussed below, we have recently increased the CE to 0.55 %/(2%BW 2πsr) from previously published[10] 0.1 %/(2%BW 2πsr). The operating conditions are, however, still not fully optimized, promising even higher CE through further optimization. As an example could be mentioned that CE of 1.04 %/(2%BW 2πsr) have been obtained for a solid-xenon target.[11] The second way to decrease the demands on the drive power was to increase the collection angle. One limiting factor for this is geometrical obscuration from source mechanics. This is especially severe for most electrically driven plasmas, where only the half-sphere portion in front of the source mechanics is unobscured and available for collection. The liquid-jet concept based on a capillary nozzle, on the other hand, show very little geometrical obscuration. An attempt to illustrate that the collection angle could be very large is made in Fig. 2. The picture should, however, be looked upon only as an illustration of the possibilities rather than a serious condenser design proposal since, for example, such a mirror could be difficult to manufacture, or it might not have a suitable NA for the rest of the system. The photo of the jet and the plasma in Fig. 3 further illustrates the good geometrical access to the plasma.

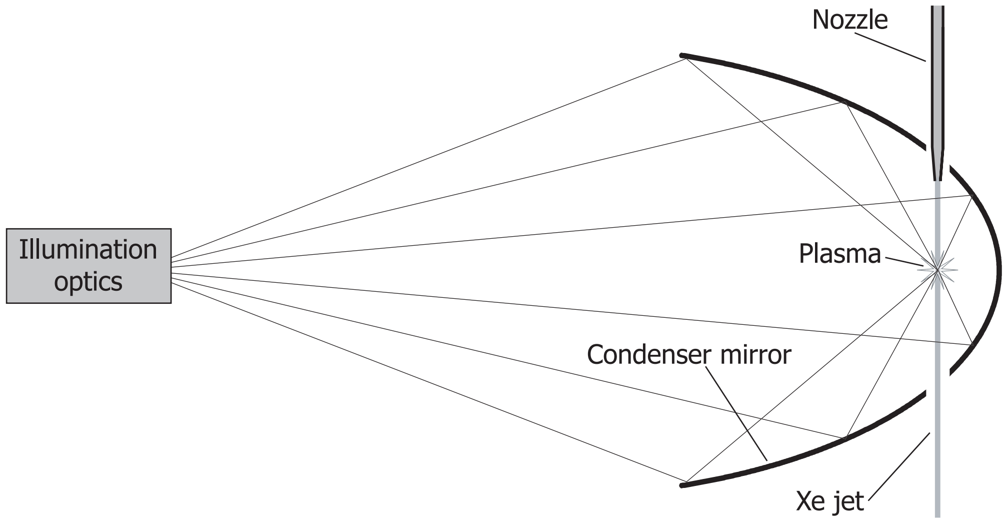

Figure 2. Illustration of how the liquid-jet-target concept using a thin capillary nozzle allows for very large collection angles.

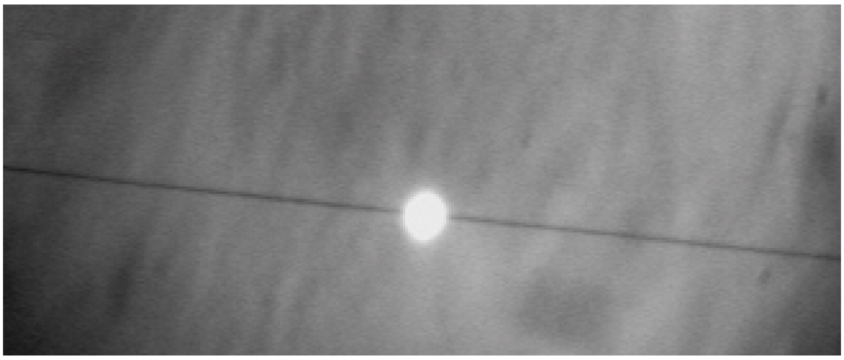

Figure 3. A photo of the xenon jet where the visible radiation from the plasma can be seen.

As was also noted in the previous section, the drive power still needs to be very high even if high CE and high collection efficiency limits the requirements. This power will give rise to severe heating of mechanical details in the vicinity of the plasma due to reemitted and scattered out-of-band radiation as well as energetic ions and atoms. It has also been shown that the plasma will erode mechanical parts such as, e.g., a nozzle in the vicinity of the plasma,[12] and that the material eroded will damage the sensitive condenser optics, thereby breaking the second main requirement of a source for EUV lithography, long mirror life time. The effect will certainly also be worse during high power operation.

One of the main properties of the liquid-xenon-jet concept is that target material is transported in a collimated fashion, allowing for plasma formation far from the nozzle. At the moment the plasma can be operated at $\sim$10 mm from the nozzle, but work is in progress to increase this distance further. It is illustrated in Fig. 4 how a liquid-jet plasma operated far from the capillary nozzle will lead to less nozzle heating and nozzle erosion than a gas-jet plasma operated close to the nozzle. The figure also illustrates how a capillary nozzle automatically meets the requirement of having a small nozzle area facing the plasma, an important parameter for the further reduction of nozzle erosion,[13] as well as reduction of thermal problems.

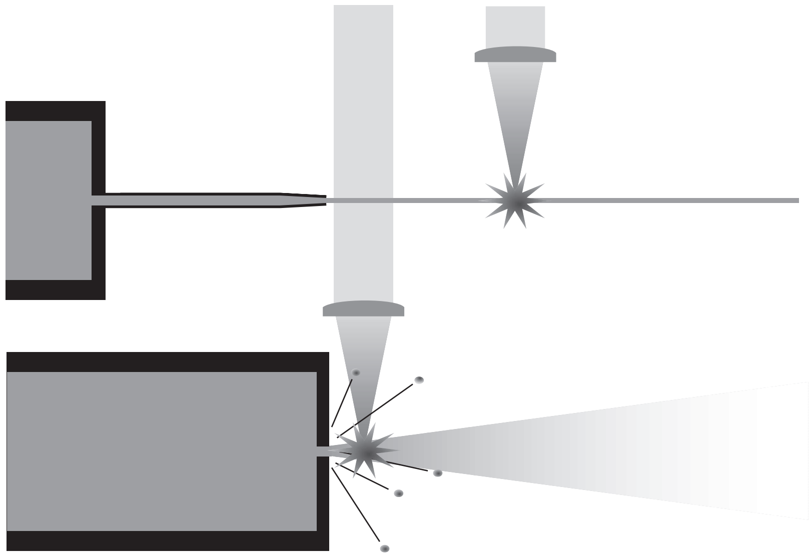

Figure 4. The plasma can be formed further from the nozzle with the liquid-xenon-jet concept than if an expanding gas or spray is used as a target. Operating far from the nozzle will limit nozzle heating and nozzle erosion. Using a capillary nozzle also reduces the nozzle area facing the plasma. This will further limit the heating and the erosion effects.

While discussing mirror contamination, one should also note that using xenon as target material and applying the liquid-jet-target method is important in order to eliminate the problem of plasma-target debris[14] associated with conventional laser-plasma sources. It is inevitable that the plasma will create some gaseous rest material, and therefore it is preferable to use a target consisting of inert atoms,[15] i.e. noble gases, so that this material will not react chemically with the sensitive mirrors. Xenon seems to be the best available target material, although its spectral emission profile is far from optimal for $\lambda \sim$13.5 nm generation as can be seen in Fig. 5. There are certainly other target materials that can be found yielding higher CE, but they will most probably generate debris, quickly destroying the mirrors. Using xenon as a target material is, however, not enough to solve the mirror contamination problems. Xenon has earlier been employed as a solid frozen target,[15] but it has been shown that a solid xenon target would result in large xenon debris fragments that will damage the multilayer mirrors.[16] Instead, the amount of debris produced can be limited by replacing conventional solid targets with, e.g., gas,[17] gas-cluster,[18] liquid-droplet[19] or liquid-jet[7,6] targets, all showing low debris generation. Among these targets though, it is only the liquid-droplet, and the liquid-jet targets that can fulfill the earlier discussed requirement of being able to operate the plasma far from the nozzle in order to reduce nozzle heating and nozzle erosion problems. The liquid-droplet technique is, however, complicated to apply to gases cooled to their liquid state. Droplet formation requires a complicated differential pumping scheme[20] since the jet will freeze long before the droplet formation point due to quick evaporation after injection into vacuum. Therefore, it is preferable to run these cryogenic liquids in the liquid-jet mode. Such a cryogenic liquid-jet laser-plasma source was first demonstrated using nitrogen.[21]

Apart from the two main requirements of high EUV power and low mirror contamination, high pulse-to-pulse emission stability of the plasma is an important factor for dose control during lithographic exposure. To achieve this, the stability of the jet must be high. We have previously reported that a method has been found to increase the directional stability of the liquid-xenon jet,[10] fundamental also for the ability to operate the plasma far from the nozzle. The dose control is also improved if the source can work at very high repetition rates, since the integrated emission of several pulses will expose each portion of the wafer. The liquid-xenon-jet travels at velocities of $\sim$50 m/s which means that new target material is continuously supplied, allowing for such high-repetition-rate operation. It

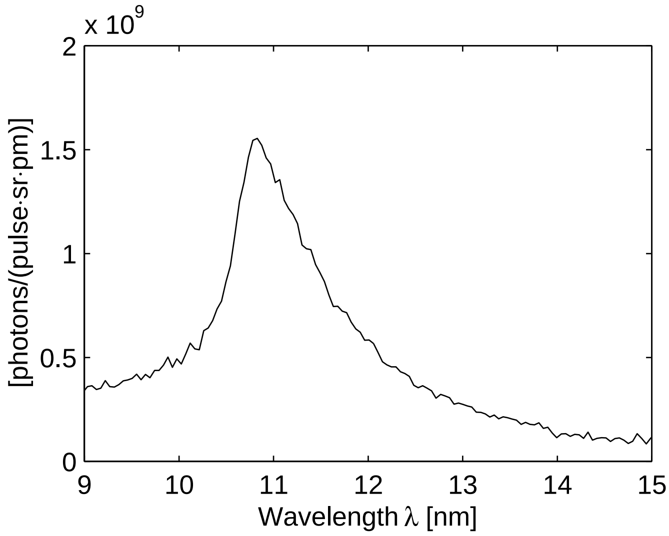

Figure 5. Single-shot emission spectra from a Xe plasma generated by a ∼5 mJ laser pulse. The spectral emission profile for xenon is not optimal for $\lambda = \sim 13.5$ nm generation, but xenon is the best available inert target material not generating harmful target debris.

has further been shown that a liquid-water-jet laser-plasma source can be operated at 250 kHz with 10% stability (2σ).[22] This is an indication that also a liquid-xenon-jet source can be operated at such high repetition-rates.

4. ABSOLUTE EUV FLUX MEASUREMENTS

Absolute measurements of the EUV flux were performed using the commercial instrument Flying Circus II (FCII)[23] which is a development of the EUV-power measurement instrument used when different EUV sources were characterized using the same tool[24,25] during year 2000.

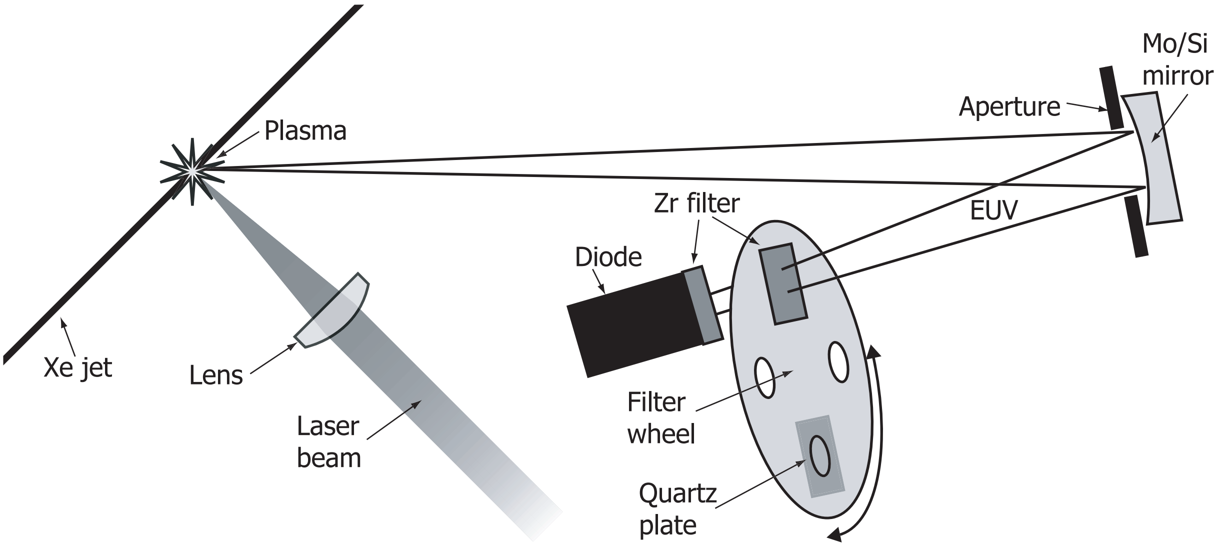

Figure 6. The tool for EUV power measurements. The use of a calibrated mirror, filter and diode makes is possible to make absolute measurements.

The function of the instrument is illustrated in Fig. 6. Radiation from the plasma is first reflected by a calibrated spherical Mo/Si multi-layer mirror at a known distance from the plasma. The mirror reflects EUV in the band-pass of the mirror as well as visible light. An aperture is mounted in front of the mirror in order to have a well-defined geometry and to limit the reflected intensity. The reflected radiation then passes a filter-wheel, present for calibration purposes described below. During normal measurements it is, however, turned so that an aperture allows the radiation to pass unobstructed. After the filter-wheel, a thin zirconium filter is present that blocks the visible light and transmits only the EUV. Finally the radiation hits a calibrated photo diode, and the signal from this diode is registered on a fast oscilloscope. Since the geometry and the efficiency of all involved components is known, the EUV power radiated by the plasma can be calculated.

With the current setup we measure conversion efficiencies of 0.55% per 2% bandwidth around 13.45 nm and into 2π steradian. The reason for publishing the data in this unit is that 2% is the bandwidth of 9 Mo/Si mirrors at $\sim$13.5 nm, which is the typical number of illumination and projection mirrors in an EUV-lithography tool, and 2π steradian is chosen for no other reason then that it seems to be the standard. A more thorough description of the calibration processes follow below.

The mirrors of FCII,[26] were supplied with a measurement report of the peak reflectivity, 68.3%, and the peak-reflectivity wavelength, 13.45 nm. The calibration was performed at the PTB facilities in Berlin. Data of a reflectivity curve, ranging 1.7 nm around the peak of a similar mirror with slightly different peak reflectivity data, was also supplied, and this curve was used to calculate the equivalent bandwidth of the supplied mirror. Another similar mirror reflectivity curve was then calculated using the software at the CXRO web-site,[27] and the throughput over the limited range of 1.7 nm around the peak was compared with the throughput over 3.6 nm around the peak, assuming the latter range to cover 100% of the total throughput. It was found that the difference is about 5%, and the equivalent bandwidth was corrected with this value to avoid an overestimation of the CE.

The EUV transmission of the filters is determined by moving in an extra filter in the light path using the filter wheel, and monitoring how this changes the signal from the diode. By then interchanging the two filters for another experiment, the transmission of both filters may be determined. In order to check that the filter really removes all the visible radiation, and does not transmit through, e.g., small pinholes, the filter wheel is turned so that the quartz plate is in the light path. It is then observed that the signal from the diode basically disappears.

The diode used is an AXUV-100.[28] The diode is reverse biased with 9 V and the signal is measured and integrated with a fast oscilloscope. The signal with the quartz plate in the path is measured in the same way and subtracted from the original in order to remove the background. The total EUV energy that hits the diode can be calculated from the resulting voltage-over-time integral created by the EUV photons impinging on the diode, using the number for the diode efficiency, 24 A/W, published by IRD.[29]

Finally, it should be noted that there is some background pressure of xenon in the vacuum system that gives rise to further absorption of in-band EUV along the light path, but since the correct pressure could not be determined with our existing pressure gauges, the measured values are not corrected for this absorption.

5. CONCLUSIONS AND FUTURE

To conclude, this paper have discussed some of the properties of the liquid-xenon-jet laser-plasma source for EUV lithography. It has been mentioned that several of the properties, including the ability to operate the plasma far from any mechanical details makes this source especially suitable for a full-scale EUV lithography tool. Work will of course continue on the improvement of all aspects of the source, although especially important is the demonstration of high-power operation. Such experiments will be done in collaboration with different laser manufacturers and reported elsewhere.

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