Characterization of a laser plasma water droplet EUV source

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ABSTRACT

We have configured a new type of target for laser plasma x-ray generation. This target consists of an in-vacuum flowing stream of liquid water droplets. We have successfully produced plasmas using this target, and have measured its extreme ultraviolet (EUV) emission spectrum. Bright lines from Li-like and He-like oxygen dominate in the plasma radiation in this region. Most importantly, no target debris related effects were observed for this type of target. A nearby Mo / Si multilayer EUV mirror suffered no reflectivity reduction at 13 nm after exposure to 10^5 laser shots on target. This observation constitutes a major breakthrough in the utilization of laser plasma radiation for practical applications, in particular, for EUV projection lithography of advanced microelectronic circuits. The simplicity and versatility of a continuously-fed target with naturally smooth surface and no associated debris problems meshes strongly with the critical engineering required for envisioned production line EUV projection lithography installations. Additionally, through the use of water based solutions as targets, it should be possible to tailor the EUV emission spectrum to match the source requirements for other potential applications, such as the x-ray microscopy.

Keywords: Laser plasma, EUV lithography, water droplet target, debris-free EUV source

INTRODUCTION

Laser-produced plasmas are recognized widely as highly favorable sources of bright EUV radiation for practical utilization in manufacturing and other applied technologies. Laser plasma sources have a strong base of commercially available hardware support, are inexpensive and much more modular in comparison to electron storage rings, and are brighter and more reproducible than pulsed power discharge sources. Implementation of laser-produced plasma sources, especially in light of current high reliability solid state laser technology, is straightforward and not technically difficult. However, two detrimental side effects have to date stalled the acceptance of laser plasmas as an EUV source in industry, the production of debris particles from the normally-used solid target and the costs associated with target material consumption and throughput. Lithography is one of the most sensitive technologies to debris production, as multilayer collecting optics are proximate to the plasma source for achieving higher collecting efficiency and are required to remain uncontaminated over long production runs. Quantitative modeling of proposed microcircuit production stations suggests 3 months running with 1J laser pulses at 1kHz repetition rate is a practical figure. This is of the order of 10^{10} shots. Given the fact that multilayer optics can be spoiled by accumulated surface debris layers of only a few nanometers thickness, severe constraints are imposed on debris production from laser plasma sources. Additionally, to be practical for industry, models have suggested target material cost figure to range around \$10,000 per 3 month run cycle, or $\$10^{-6}$ per shot. No credible solid material target has been demonstrated or proposed that even remotely approaches this cost criterion. This is not to even mention the formidable logistical difficulty of solid material feedthrough at a high volume rate into a vacuum system running continuously for as long as three months. As a result of the debris and cost issues attendant to laser plasma EUV sources, the tendency has been to dismiss their considerations for practical use, despite their otherwise attractive properties.

At CREOL, we have been quantitatively documenting and seeking to address these collateral problems with laser plasma sources. Two years ago, we proposed the concept of a mass-limited cryogenic target [1]. Such a target is matched in aerial density and spatial size to the laser focal spot, so that all target atoms contribute to the plasma with no excess. Further, the target is sufficiently volatile in its condensed form that in a room temperature vacuum, the material would quickly evaporate or sublimate. These two attributes of the mass-limited cryogenic target mitigate against large-particle debris and adhesion to the multilayer reflector surface, respectively. Since the first proposal, a number of investigations have been conducted by various groups, including work on frozen xenon pellets [2], ethanol jets [3] and water ice[4, 5, 6] Water ice is particularly interesting because it is extremely inexpensive and its plasma emission in the EUV are principally strong isolated lines of Li-like and Ne-like oxygen ions. A number of these lines are grouped near 13nm, the relevant wavelength for projection lithography due to the availability of high reflectivity multilayer mirrors at this wavelength. In the water ice target experiments, x-ray conversion into a 0.3 nm bandwidth (the passband of multilayer optics for lithography) at 13 nm relative to incident laser light energy was measured to be about 0.6%, about half that of the most efficient conversion material, tin. However, unlike a tin target, no decrease in multilayer reflectivity was seen after an accumulated 10^4 shots from a multilayer mirror located 7.5 cm from the plasma.

In our current investigation, we again use water as a source material, but for the first time, we report both spectral and debris effect results from a liquid water droplets stream target. Liquid water is a natural extension of this target study. It is inexpensive, capable of being continuously fed into the laser interaction volume, and is unstable to evaporation under vacuum at room temperature. We believe by our experimental results that we have demonstrated a proof of principle of a practical laser plasma target for industrial applications, and in particular, for EUV projection lithography.

EXPERIMENTAL RESULTS

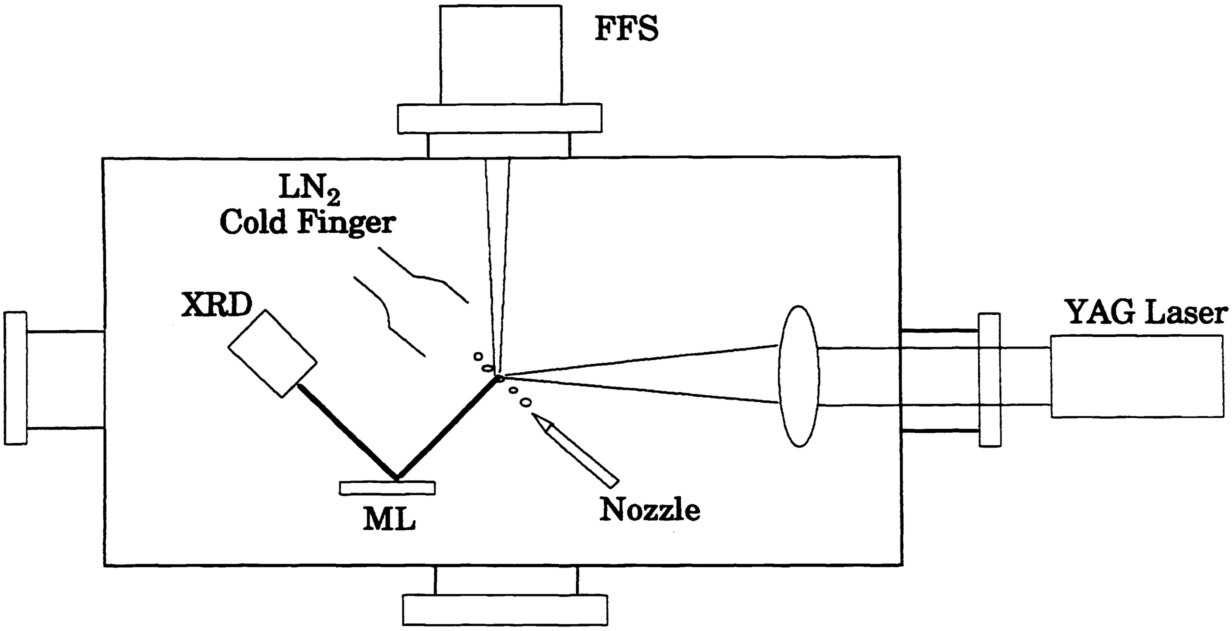

Figure 1, Experimental setup

Figure 1 is a sketch of the experimental setup. A vacuum feedthrough supplies a continuous flow of chemically pure water from an external reservoir to a piezo-electrically driven nozzle, which drives a jet of streaming liquid water droplets into the laser interaction region at the center of the vacuum chamber. The laser is synchronized to the jet system through the piezo controller to ensure that every laser pulse hits the center of one of the droplets. The laser pulses from a commercial YAG laser system (300 mJ energy / pulse, 10 ns time duration @10 Hz repetition rate and 1.06 μm) enter through a quartz window and are focused down by an F/2 lens to a minimum spot size of approximately 100 μm diameter. The peak laser intensity at the focus is in the low 10^{11} W / cm^2. Our nozzle works in the mode of continuous drop operation [7], which breaks into droplet at the repetition rate of 1MHz, so 10^6 water droplets are produced per second, the overwhelming majority of these droplets are unused and constitute a potentially severe vapor load to the vacuum system. Therefore we have placed a cold condensation surface, a liquid nitrogen "cold finger", for residual water. As a result, the pressure in the chamber can be maintained at 10^{-4} Torr with only modest pumping (240 L / s turbo pump) during continuous operation of the jet and 10^{-6} Torr when the jet is off. A flat-field x-ray spectrograph (FFS) is attached to the chamber, which disperses the plasma radiation in the region of 5 - 20 nm onto a flat focal plane. The resolution of the spectrograph is 0.6 nm/mm. A Be-filtered silicon x-ray diode (XRD) is placed in the system after a Mo / Si multilayer mirror to monitor the change of the reflected EUV signal versus the number of laser shots. The multilayer mirror is placed 4 cm away from the laser plasma spot and reflected at 45° to the XRD diode. The droplet stability is measured to be within ±5 μm in both directions along and perpendicular to the jet's propagation. The water flow rate of the jet system is measured to be 0.23 mL / min., corresponding to a jet velocity of about 50 m/s for 10 μm diameter nozzle. The diameter of the droplet, d_d, is related to the diameter of the nozzle, d_n, by $d_d = 1.89\ d_n$, which is about 20 μm for $d_n = 10$ μm. The separation between two adjacent droplets is therefore about 50 μm. Because of the large spot size of our laser system, three of the droplets are usually captured by the laser beam simultaneously with one at the center and the other two at both sides of the low intensity wings of the laser beam. This represents the worst situation from the consideration of debris generation since significant amount of debris is believed to be generated from the cooler region of the plasma, i.e., the lower intensity wings of the laser beam.

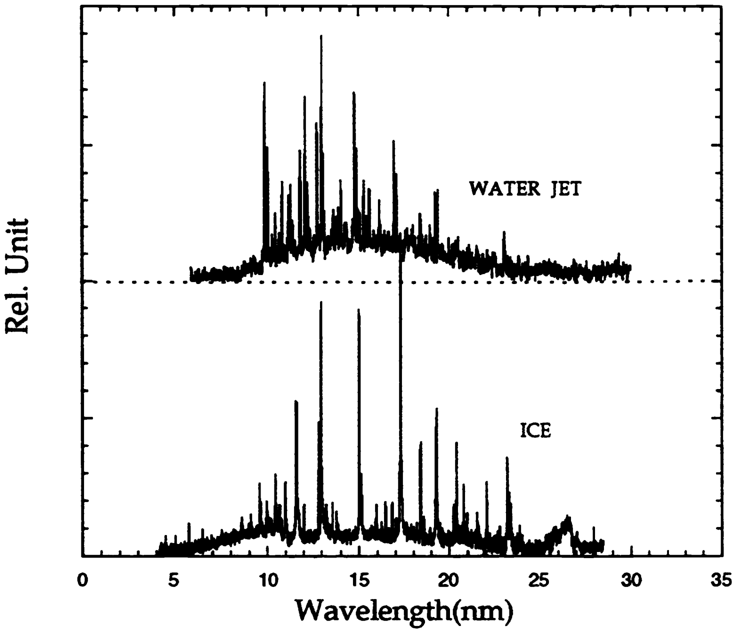

Figure 2, The EUV spectra from bulk ice target and water droplet target

The comparison of the x-ray spectra from both water jet plasma and bulk ice plasma is shown in Fig. 2. The top portion of this figure is from water jet and bottom portion from a bulk ice target irradiated with a 5 J Nd$^+$ Glass laser [5]. The spectra from the water jet has more lines in the 10 - 15 nm region than the bulk ice target, which indicate that this plasma has relative lower temperature, but the similarity of both spectra in terms of the position of the lines in the region of 7 - 15 nm also suggests that some part of the plasma has reached a temperature high enough to produce He-like and Li-like oxygen ions (around 25 eV). Therefore increasing the laser energy per pulse, improving the quality of the laser beam and reducing the focal spot size to match the size of the water droplet will increase the laser intensity and raise the plasma temperature to the point where Li-like and He-like ions would be dominant and thus increase the EUV conversion efficiency to be 0.3 nm bandwidth at 13 nm..

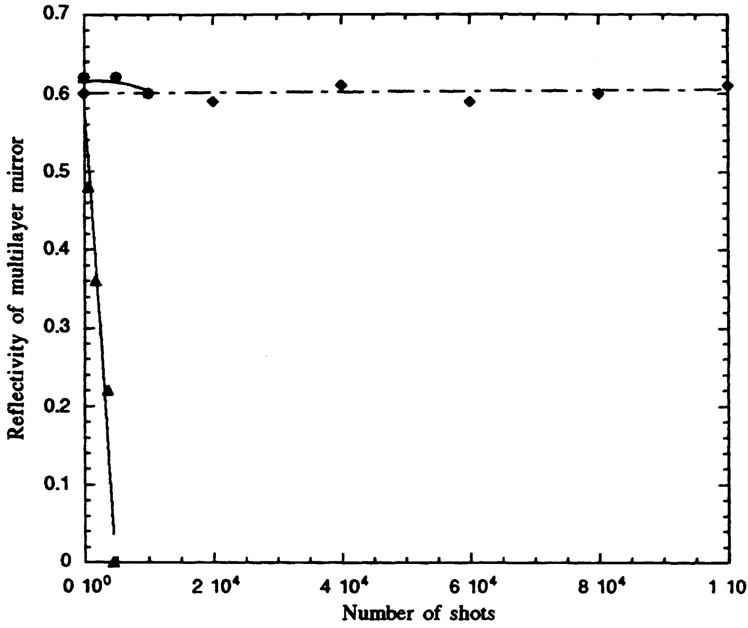

Figure 3, Relative multilayer reflectivity vs. the number of the laser shots

Figure 3 is the plot of the relative multilayer reflectivity versus the number of laser shots for the water droplet target, the ice target and the solid metal target. The same plot for bulk ice and solid tin target up to 10^4 laser shots has been presented in Reference 5. The maximum number of laser shots on the water jet target has reached 10^5, one order of magnitude more than for Ref. 5. This number corresponds to an approximate equivalence in the lithographic configuration of $> 2 \times 10^6$ shots, since for this configuration, a distance of 20 cm between the plasma source and the first mirror is assumed and the debris density is supposed to decrease as $1 / r^2$. Even this number is still four orders of magnitude less than the final goal of 10^{10} for the three months of continuous operation at 1 kHz. But the flatness of the curve throughout the whole range shows no evidence of reflectivity reduction.

Table 1 lists both raw material costs in \$/gm and the material cost per million shots assuming 6.5 x10^{16} atoms needed per shot for the case of mass-limited target. Only iron, copper and water targets are under the price limit of \$1 per million shots. But there exists potential problems in feeding the solid target materials into vacuum chamber in the rate of ~1 mm^3/s and the cost for doing this will easily bring the cost to pass the limit.

Table 1, Target material costs

Z	Name	\$/gram	Cost for single shot
78	Pt	84.9	1.34E-03
79	Au	83.6	1.33E-03
58	Ce	11.52	1.30E-03
4	Be	588.1	4.29E-04
81	Ti	23.85	3.95E-04
49	In	7.22	6.72E-05
73	Ta	2.04	3.00E-05
50	Sn	2.47	2.37E-05
74	W	1.5	2.23E-05
54	Xe	1.535	2.16E-05#
30	Zn	2.53	1.34E-05
82	Pb	.586	9.80E-06
3	Li	9.21	7.00E-06
42	Mo	.48	3.74E-06
12	Mg	1.68	3.27E-06
48	Cd	.33	2.97E-06
36	Kr	.267	2.40E-06#
13	Al	.137	3.01E-07
26	Fe	.048	2.20E-07
29	Cu	.03	1.82E-07
18	Ar	.0022	9.50E-09
	H2O	.0055	8.00E-09 *
* Data from Fisher Scientific			
# Data from Liquid Carbonic			
Other Data from Goodfellow			

CONCLUSIONS

We have successfully set up a low cost, low debris, line-emitting water jet laser plasma EUV source system for projection lithography. We have demonstrated no reduction in reflectivity from a multilayer reflector at 4 cm from the plasma over 10^5 shots of operation. The experimental results demonstrate that this system has the potential to achieve the final goal for projection lithography source: three months continuous operation at unit cost of \$$10^{-6}$ per shot and a throughput of 60 x 6" wafer per hour at an x-ray conversion efficiency of approximate 0.6%, comparable to heretofore standard metal targets.. Moreover this water jet system has the possibility to work with other non-clogging liquid compositions to match the particular application need.

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