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Liquid-jet target laser-plasma sources for EUV and X-ray lithography

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We describe a new high-brightness laser-plasma source for X-rays and extreme ultraviolet (EUV) radiation. By utilizing a liquid target the harmful emission of debris is significantly reduced or completely eliminated. The spectrum can be spectrally tailored by choosing a suitable liquid. We also show the possibilities to extend the debris-free source to liquid solutions of solids and to liquefied gases. This results in new emission wavelengths and offers the possibility to increase conversion efficiency. We believe that this new source is a suitable choice for EUV lithography as well as for proximity X-ray lithography.

1. INTRODUCTION

The laser-produced plasma offers a compact and relatively inexpensive high-brightness source for X-rays and extreme-ultraviolet (EUV) radiation [1]. The major drawback has been emission of debris, i.e., small fragments and particles, which may destroy sensitive components (e.g., masks) positioned close to the plasma. We have developed a new type of laser-plasma based on a liquid target. Compared to conventional solid-target laser plasmas this arrangement has several advantages. By eliminating the debris problem sensitive components can be positioned close to the source without risking contamination or damages. This increases the useful flux and reduces exposure time. The liquid-target is also regenerative (which makes it possible to perform full-day operation without interrupts), it emits radiation almost uniform in space and can provide fresh target material at very high (MHz) rates.

2. THE LIQUID-TARGET LASER-PLASMA X-RAY SOURCE

2.1 Basic arrangement

The liquid-target laser plasma is thoroughly described elsewhere [2,3]. Below follows a brief summary. The basic schematic arrangement is shown in Fig 1. The beam from a pulsed high-power laser (currently frequency-doubled Nd:YAG, 10 Hz, 70 mJ, 100 ps) is focused to a small spot (θ~12 μm). The target material is generated by forcing a liquid through a glass capillary nozzle. Minimization of surface energy results in spontaneous breakup of the microscopic jet into droplets. Two different methods can be applied. For liquids with suitable hydrodynamic properties the laser pulse is synchronized with a piezoelectrical vibration of the nozzle. This makes it possible to hit a single droplet with each laser pulse. Another alternative, applicable for liquids with low surface tension, is to focus the beam directly on the jet before breakup. Both methods lead to a target of the same size as the laser focus thereby significantly reducing the debris emission.

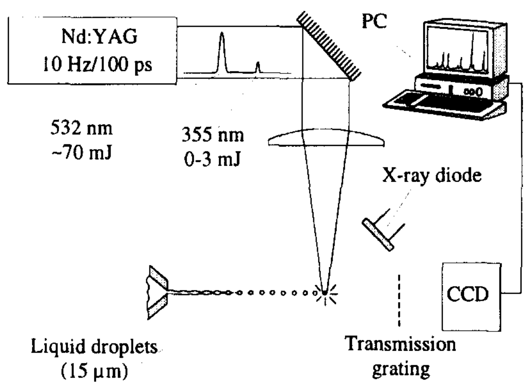

Figure 1. The basic arrangement for the liquid-target laser-plasma X-ray source.

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The flux from the plasma is typically $0.3\text{-}1\cdot10^{12}$ photons/(sr·line·pulse) and it can be increased a factor of 3 with the use of a small prepulse [4]. For emission of soft X-rays and EUV radiation the emission is strongly dependent on compound and it can therefor be spectrally tailored by the choice of target material. We have investigated and characterized many different liquids with respect to radiation and any possible debris emission. Compared to conventional laser-plasma sources the liquid-target LPP show similar X-ray/EUV emission, however the emitted debris is reduced several orders of magnitude or, for liquids which only contain compounds that form gases after evaporation, completely eliminated [5].

2.2 Liquid target based on solutions of solids

Although many different elements can be addressed when using a liquid target some emission wavelengths are impossible to generate without using solid compounds. We are therefore investigating the use of liquid solutions of solids as target for our laser-plasma X-ray source. With a urea/water target the emission from helium-like nitrogen line at λ=2.88 nm was determined to be $1\cdot10^{12}$ photons/(sr·line·pulse) [5]. Metals like sodium and copper can be used when dissolving their salts in a suitable liquid. Since conversion efficiency increases with atomic number many different compounds can be of interest.

2.3 Liquid target based on cryogenically cooled gases

It is also possible to extend the liquid target to compounds which are gases under normal conditions, i.e., room temperature and atmospheric pressure. It is difficult to reach high density in a gaseous target, however when cooling and/or increasing the pressure all gases become liquids. We are using this to create high-density liquid jets for laser-plasma X-ray generation. With a liquid nitrogen target the detected emission from the helium-like nitrogen line at λ=2.88 nm was $\sim5\cdot10^{11}$ photons/(sr·line·pulse) [6]. As expected, no debris at all could be detected from this target. Some different gases are currently investigated. For example, oxygen, argon, xenon and krypton might be of interest.

3. SOURCES FOR EUV LITHOGRAPHY

Several different compounds can be considered for emission in the EUV range (10 nm<λ<15 nm). We have shown that strong emission from oxygen ions can be achieved when using a water/methanol target. With a frequency-doubled 750 mJ, 8 ns Nd:YAG laser $\sim4\cdot10^{12}$ photons/(sr·line·pulse) were detected for the lithium-like oxygen 2p-4d line at λ=13.0 nm7. The high conversion efficiency and potential low debris emission from xenon makes this target interesting. Xe have many emission lines in the EUV range.

4. SOURCES FOR PROXIMITY X-RAY LITHOGRAPHY

With proper laser parameters it is possible to generate X-ray emission ~1 nm (1.2 keV), which is suitable for proximity XRL. Figure 2 shows a part of the spectrum from a liquid fluorocarbon laser plasma. The conversion efficiency into useful X-rays between λ=1.2 nm an λ=1.7 nm, i.e. 0.7-1 keV, has been determined to 5 % [8].

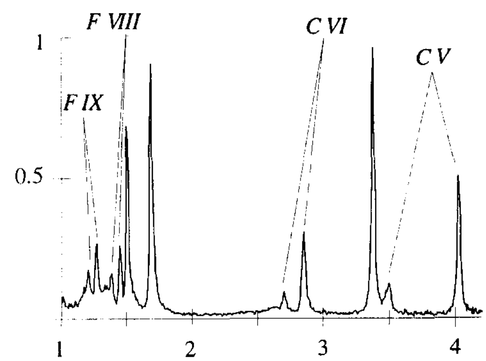

Figure 2. X-ray emission from a fluorocarbon liquid.

In order to demonstrate the source's feasibility for lithography, exposures of a test pattern were performed. The mask consisted of 200 nm gold structures on a 250 nm silicon nitride membrane. Sub 100 nm structures with high aspect ratio were obtained after 20 minutes exposure of a chemically amplified resist (SAL-601 ER 7) [9]. Current work aims at producing shorter wavelengths with high conversion efficiency. We are also implementing a 100 Hz laser into the system, thus allowing for 10 times shorter exposure times.

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REFERENCES

1. See, e.g., *OSA proceedings on soft X-ray lithography Vol. 18*, eds. A. M. Hawryluk and R. H. Stulen (Optical Society of America, Washington DC 1993).
2. L. Rymell and H. M. Hertz, Opt. Commun. **103**, 105 (1993).
3. H. M. Hertz, L. Rymell, M. Berglund, and L. Malmqvist, in *X-ray Microscopy and Spectromicroscopy,* eds. J. Thieme, G. Schmahl, E. Umbach, and D. Rudolph (Springer, Heidelberg 1997), V-3.
4. M. Berglund, L. Rymell, and H. M. Hertz, Appl. Phys. Lett. **69**, 1683 (1996).
5. L. Rymell, M. Berglund, and H. M. Hertz, Appl. Phys. Lett. **66**, 2625 (1995).
6. M. Berglund, L. Rymell, H. M. Hertz, and T. Wilhein, Rev. Sci. Instrum. **69**, 2361 (1998)
7 L. Malmqvist, L. Rymell, and H. M. Hertz in *Extreme Ultraviolet Lithography, OSA Trends in Optics and Photonics Vol. 4*, eds. G. D. Kubiak and D. R. Kania (Optical Society of America, Washington DC 1996), 72.
8. L. Malmqvist, L. Rymell, H. M. Hertz, Appl. Phys. Lett. **68**, 2627 (1996).
9. L. Malmqvist, A. L. Bogdanov, L. Montelius, and H. M. Hertz, J. Vac. Sci. Technol. B 15, 814 (1997).