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Supersonic Cluster Jet Source For Debris-Free Extreme Ultraviolet Production

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SUPERSONIC CLUSTER JET SOURCE FOR DEBRIS-FREE EXTREME ULTRAVIOLET PRODUCTION

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ABSTRACT

The supersonic cluster jet has been developed and characterized for use as a target medium to produce a clean source of extreme ultraviolet radiation for extreme ultraviolet lithography and other applications. Spectroscopic characterization of the laser plasma emission produced from Xe, O₂ and Kr cluster gas targets has been performed. Xe is the most efficient target gas, exhibiting a conversion efficiency at 13.5 nm of 0.8% into the relevant 2.5% spectral bandwidth. The other target gases are less efficient in the spectral region of interest and, in the case of oxygen, emit ~5 times less off-band radiation. The angular distribution of the Xe plasma emission has also been characterized.

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CONTENTS

Introduction	7
Source Alternatives for Extreme Ultraviolet Lithography.....	7
Background of laser plasma sources for EUVL	8
Cluster Jet EUV Source	8
Cluster jet plasma spectroscopy.....	9
Angular distributions of Xe plasma emission	11
Summary and Conclusions	12
References	14
Appendices.....	15
Figures	
1 Schematic diagram of the cluster jet laser plasma source, EUV monochromator for plasma emission spectroscopy, and rotary detector platform for measuring source emission angular distributions.	9
2 Normalized Xe cluster jet laser plasma emission spectrum compared to spectrum produced from a solid gold target under identical conditions. See text for nozzle stagnation conditions.....	10
3 Laser plasma emission spectra of O ₂ and Kr target gases. See text for nozzle stagnation conditions.....	11
4 Angular distribution of Xe cluster jet laser plasma in the Be filter 70-108 eV spectral pass-band. In this figure, the jet beam axis is oriented into the page, the laser plasma is located at the origin and the laser propagation direction proceeds from 0° to 180°.....	12

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Supersonic Cluster Jet Source for Debris-Free Extreme Ultraviolet Production

I. Introduction

Ia. Source Alternatives for Extreme Ultraviolet Lithography

Production of Extreme ultraviolet (EUV) light for Extreme Ultraviolet Lithography (EUVL) can be accomplished in principle by laser-produced plasma sources, synchrotron radiation sources, and electric discharge sources. The strengths and weaknesses of each of these approaches are briefly reviewed below. Additional methods to produce EUV radiation include high-harmonic generation with femtosecond laser pulses, discharge-pumped x-ray lasers, and electron-beam driven radiation devices, although none of these methods appear likely to achieve the 30-40 W levels of in-band source power at modest cost required in manufacturing and will not be discussed further.

Laser-produced plasma sources are the most mature compact EUV source alternative for EUVL. These point-like sources convert 0.8-3.2% of the incident laser power into EUV light in the required spectral bandwidth and are of modest size. Due to the small (~200 μm) source size, condensers have been designed that collect up to 35% of this in-band power and deliver it to the mask of a scanning ring-field projection optic. High-repetition-rate (3000 - 6000 Hz) pulsed laser drivers that deliver 1500 W of focused power to the target region will be required to meet throughput requirements, and these are actively being developed commercially. The footprint of the high-power laser plasma source now under development is modest at 4 ft. x 6 ft. for the 1500 W drive laser and 4 ft. x 3 ft. for the cluster gas target system, including vacuum chamber and pumps. The cost and complexity of the integrated laser and target light source system is expected to be high compared with sources employed in manufacture today, and is thus an issue. Condenser reflectance loss from source particles, a tremendous issue in earlier laser plasma sources, has been reduced by a factor of over 100,000 through the use of gas cluster targets. While additional 10-20 fold improvements are needed in this area, significant strides continue to be made in ongoing source R&D. For example, recent nozzle modification studies resulted in a factor of 4.5 further reduction in particle deposition rates on plasma-facing condensers.

Synchrotron radiation sources represent another mature candidate technology for EUVL. They can be made very reliable and have no issues with debris, although they are not compact and have unique and costly facilities requirements. A significant issue regarding the use of synchrotrons for EUVL is that these sources emit broad-band EUV power that achieves high brightness in the narrow vertical axis, but low brightness in the extended horizontal plane. Thus, it is not presently known how to extract sufficient in-band power to achieve acceptable throughput with a scanning ring-field projection optic. Several patents and publications have appeared describing high-efficiency synchrotron condenser designs that attempt to do this, but these remain a factor of 2-3 below laser plasma source projections.

Electric discharge EUV sources are potentially the simplest and least expensive alternative for EUVL, but very little work has been done to develop and characterize their performance. These sources employ high-voltage, high-current discharge pulses to form 15-50 eV plasma in a gaseous media such Li vapor, Xe or oxygen. Theoretical predictions and early experiments for the 13.5 nm 2-1 transition in hydrogen-like Li suggest that wall-plug efficiencies near 10% are possible in sub-mm emission volumes. To date, these sources have exhibited low EUV production efficiencies and low repetition rates, however. Increasing repetition rates to 1000 Hz and eliminating the deleterious effects of eroded wall material present significant challenges. Development of discharge prototypes is in progress, including a detailed assessment of each of these issues. The 5-10 fold decrease in source cost and complexity that might be achieved with a successful high-power EUV discharge source remains very attractive.

Ib. Background of laser plasma sources for EUVL

Early work on laser plasma sources concentrated on the EUV emission properties, such as conversion efficiency, source size and angular distribution. Conversion efficiency (CE) is defined as the fraction of generated EUV energy in a given spectral bandwidth divided by the laser energy. A wide range of solid metal targets such as Au, Ta, W, and Cu achieved CEs in the range from 0.5 - 1% in a 2.3% bandwidth, with Sn exhibiting the highest at 2%[1].

Printing of 0.1 micron EUVL patterns exposed with a laser plasma source was first demonstrated in 1991 with a gold target.[2] At that time, short condenser lifetime due to the deposition of target debris was a serious impediment. Debris mitigation measures were developed to increase condenser lifetimes by a factor of ~1000x in the various EUVL exposure tools[3], but these were not adequate for manufacturing environments. Non-metallic targets such as frozen Xe pellets[4] and water droplets[5] were also developed, but impact damage of the multilayer mirrors by high-momentum solid or liquid fragments remained an issue.

II. Cluster Jet EUV Source

The cluster jet plasma source was developed beginning in 1994. A Sandia patent for the concept, entitled "Cluster beam targets for laser plasma extreme ultraviolet and soft x-ray sources", was issued in November, 1996. The source employs as the target medium a stream of high-density van der Waals clusters of inert gas such as xenon, produced by isentropic expansion of the gas from 10-15 atm pressure through a 250 μ m cooled nozzle into vacuum[6]. The clusters provide a medium of dispersed solid-density targets, achieving excellent energy extraction (>90%) from the focused drive laser to produce the heated plasma. Due to the complete vaporization of the weakly-bound clusters during the laser pulse, the cluster jet source produces no fragments or particulate debris, in contrast to traditional solid targets. CE measurements have shown that this source is as efficient at 13.5 nm as sources based on Au targets, converting 0.8% of the drive laser pulse energy into in-band EUV energy. At the same time, the reflectance loss rate of multilayer-coated

condenser optics placed 10 cm from the source has been reduced to 10% after 10^8 plasma pulses, a factor of $>100,000$ improvement over earlier Au targets.

During this LDRD, work on the supersonic cluster EUV source concentrated on two areas: the spectroscopy of the cluster jet plasma emission and the characterization of the angular distribution of that emission. Spectroscopic characterization is needed to establish the amount of in-band EUV power available as a function of wavelength. The choice of specific operating wavelength for maximum throughput and critical dimension (CD) control in the EUVL tool will then depend on the trade-offs between wavelength variations in source power, multilayer mirror reflectance, resist response, and projection optic design. Knowledge of the emission angular distribution is required to design efficient large-solid-angle condensers to collect and deliver the greatest possible fraction of EUV to the mask and into the EUVL projection optic.

IIa. Cluster jet plasma spectroscopy

Spectroscopic characterization of the cluster jet plasma emission was performed with a high-throughput EUV/Soft X-Ray monochromator, shown schematically in Fig. 1 and described previously [7]. Spectra were recorded by averaging 10 laser plasma pulses per wavelength increment with a filtered XUV 100C silicon photodiode and scanning the monochromator grating over the spectral region of interest. The resulting

Figure 1. Schematic diagram of the cluster jet laser plasma source, EUV monochromator for plasma emission spectroscopy, and rotary detector platform for measuring source emission angular distributions.

spectrum is then normalized by the known spectral response function of the monochromator to account for the variation of efficiency as a function of wavelength.

Figure 2 shows such a spectrum for Xe cluster jet plasma emission collected for a 250 μm nozzle, 400 psi stagnation pressure, nozzle temperature of 218 K and incident laser intensity of $\sim 1 \times 10^{12} \text{ W/cm}^2$. As can be seen, the emission shows several absorption features between 13 - 15 nm. These have been identified previously by Carroll and O'Sullivan [8] who have shown that the weak absorption dips near 13 nm correspond to various transitions in Xe VI, VII, and VIII.

Figure 2. Normalized Xe cluster jet laser plasma emission spectrum compared to spectrum produced from a solid gold target under identical conditions. See text for nozzle stagnation conditions.

Plasma emission spectroscopy was also performed on O_2 , a mixture of 80% N_2 /20% O_2 (air) and Kr target gases. These gases were chosen because they have known transitions in the EUV region of interest, significantly lower cost than Xe, and offer the possibility of less EUV emission in spectral regions outside of the multilayer reflectance bandwidth, so-called "off-band emission." Off-band emission contributes to condenser mirror heating and resulting thermo-optical distortion and should be minimized. Figure 3 plots representative spectra obtained for O_2 and Kr, again normalized by the spectral response function of the monochromator. It is found that oxygen can be made to emit $\sim 50\%$ of the flux that Xe does near 13 nm and emits five times less off-band power. The 80% N_2 /20% O_2 mixture (not shown) is dominated by the oxygen ion transitions but is a factor of two weaker than the emission produced by oxygen alone. The Kr plasma spectrum exhibits pronounced emission features near 10 nm, below the reflectance regions of both Mo/Si and Mo/Be multilayer mirrors. Although all of these target gases are significantly less expensive than Xe, and emit less deleterious off-band radiation, none of them can match the efficiency of Xe and thus do not appear to be competitive with Xe for commercial EUVL.

Figure 3. Laser plasma emission spectra of O_2 and Kr target gases. See text for nozzle stagnation conditions.

IIb. Angular distributions of Xe plasma emission

To establish the most efficient range of angles over which the cluster jet plasma emission can be collected by a condenser, the angular distribution of the emission was measured. The measurement was made with a filtered XUV 100C detector mounted on a rotating platform. The detector was rotated about the plasma at a distance of 10 cm in a plane containing the plasma and the incident laser and orthogonal to the cluster jet flow axis. Figure 4 shows a representative angular distribution recorded in the Be filter spectral transmission band from ~ 70 -108 eV. The plasma is located at the origin in this plot, and the laser beam is entering from the 0° direction. As can be seen, the angular distribution is reasonably well approximated by the function $\sin(\theta - 60^\circ)^{0.33}$, a form that has been seen for emission from solid targets. In contrast to solid targets, which emit only into a 2π steradian solid angle with no radiation appearing on the opposite side of the irradiated region (i.e. "behind" the target), a significant fraction of the total EUV produced by the jet plasma radiates in this region. The reason for this is presumably due to the fact that the cluster jet beam opacity is finite, unlike the infinite opacity of the solid target. The fact that the emission peaks in the 60° direction is somewhat arbitrary and is due to the signal optimization procedure used for this specific experiment. Subsequent experiments have shown that the emission peak can be shifted to lie along the laser propagation axis (0°) simply by translating the jet beam slightly with respect to the fixed laser focus.

Figure 4. Angular distribution of Xe cluster jet laser plasma in the Be filter 70-108 eV spectral pass-band. In this figure, the jet beam axis is oriented into the page, the laser plasma is located at the origin and the laser propagation direction proceeds from 0° to 180°.

III. Summary and Conclusions

The EUV spectroscopic emission properties of cluster jet laser plasmas have been characterized for Xe, O₂, 80%N₂/20%O₂, and Kr target gases. Xe is found to be the most efficient emitter, producing 0.0035 J/eV of 13.5 nm radiation per joule of incident laser energy. O₂, 80%N₂/20%O₂, and Kr target gases are typically less than half as efficient as Xe throughout the range from 11-14 nm. The spectra of these latter target gases are dominated by line radiation, producing approximately one-fifth as much off-band radiation as Xe does. The angular distribution of EUV radiation produced by the Xe plasma is found to vary approximately as $\sin(\theta - 60^\circ)^{0.33}$, a form that has been seen for emission from solid targets. Unlike solid targets, however, significant cluster jet plasma EUV emission is observed over a full 4π steradians, not only into 2π steradians.

The status of the laser plasma source for commercial EUVL is solid, with high-power engineering demonstrations underway. At the same time, it is clear that significant technical and commercialization issues remain. None of these issues represents a fundamental show stopper, but will require a continued focused commitment to resolve them. Source scale-up, increased condenser life, and reliability have all shown significant improvement over the past year. In addition, widespread availability of the source is being made possible through the engagement of commercial laser and cluster jet suppliers to develop and commercialize these key source components.

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APPENDIX A — List of publications, presentations, patents, and invention disclosures

Publications: None

Presentations:

G. D. Kubiak, Optical Soc. of America National Symposium, Rochester, NY, Oct. 21-25, 1996. (Invited).

Invention disclosures: None

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