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High-power extreme ultraviolet source based on gas jets

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ABSTRACT

We report on the development of a high-power laser plasma extreme ultraviolet (EUV) source for Extreme Ultraviolet Lithography. The source is based on the plasma emission of a recycled jet beam of large Xe clusters and produces no particulate debris. The source will be driven by a pulsed laser delivering 1500 W of focused average power to the cluster jet target. To develop condensers and to optimize source performance, a low-power laboratory cluster jet prototype has been used to study the spectroscopy, angular distributions, and EUV source images of the cluster jet plasma emission. In addition, methods to improve the reflectance lifetimes of nearby plasma-facing condenser mirrors have been developed. The resulting source yields EUV conversion efficiencies up to 3.8 % and mirror lifetimes of ~10^9 plasma pulses.

I. INTRODUCTION

Commercial sources of extreme ultraviolet (EUV) light for Extreme Ultraviolet Lithography (EUVL) will be required to produce at least 40 Watts of in-band EUV power without significantly damaging nearby condenser optical elements and run reliably for 1000-2000 hours. A new laser plasma source approach employing a recycled dense beam of large Xe_n van der Waals gas clusters ($n \geq 100{,}000$) as the target medium is being developed to meet these power, source cleanliness, and reliability requirements. The cluster beam target is to be irradiated with 1500 W of pulsed laser power, producing a point-like plasma radiator yielding 12 - 48 W of EUV power, depending on wavelength. These clusters locally yield an electron density greater than the critical density necessary for efficient laser absorption and plasma heating. Each cluster is small enough, however, to be completely vaporized within the 5-10 ns incident laser pulse duration, completely eliminating the microscopic particulate "debris" that has plagued earlier laser plasma sources.

In the present study, we describe the spectroscopy, angular distributions, and source images of the cluster jet plasma emission under typical conditions. Spectroscopic characterization has been performed to establish the amount of in-band EUV power available as a function of wavelength and to understand plasma dynamics. The choice of specific operating wavelength for maximum throughput and critical dimension (CD) control in the EUVL tool depends in part on the wavelength dependence of the source power, but also on the wavelength dependence of multilayer mirror reflectance, resist response, and projection optic design. Emission angular distributions and source images have been characterized to enable the design of condenser systems.

In addition to the plasma radiative properties, we have also investigated methods to reduce nozzle erosion and deposition on nearby condenser optics to increase condenser lifetimes. Although the cluster jet source does not produce particulate debris directly, our earlier studies revealed that the jet nozzle is eroded slowly by energetic plasma ions and neutrals[1] and that this eroded nozzle material slowly forms obscuring deposits on nearby condenser mirrors. Thus, we have developed new approaches that greatly reduce nozzle erosion and subsequent deposition rates.

The remainder of the paper is organized in four sections. Section 1 briefly reviews laser plasma sources, section 2 describes the cluster jet source and its optimization, section 3 presents EUV spectroscopy, emission angular distributions, and emission source size, and section 4 describes the characterization and reduction of nozzle erosion and deposition.

Ia. Laser Plasma Sources for Extreme Ultraviolet Lithography

Laser-produced plasma sources are the most mature, compact source alternative for EUVL. These point-like sources convert up to 3.8 % of the incident laser power into EUV light in the required spectral bandwidth and are of modest size. 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 2.5 % bandwidth, with Sn exhibiting the highest at 2 %[2].

Printing of 0.1 micron EUVL patterns exposed with a laser plasma source was first demonstrated in 1991 with a gold target[3]. 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[4], but these were not adequate for manufacturing environments. Non-metallic targets such as frozen Xe pellets[5] and water droplets[6] were also developed, but impact damage of the multilayer mirrors by high-momentum solid or liquid fragments remained an issue.

To meet throughput requirements, we are currently developing a high-power laser plasma source, scaling up its average power to deliver ≥ 40 watts of EUV in a 2.5% bandwidth over 2π steradians. A high-repetition-rate pulsed laser driver that delivers 1500 W of focused power to the target region is being developed commercially for this purpose. Condensers are being developed that collect ~ 30% of the in-band power and deliver it to the mask of a scanning ring-field projection optic. Condenser reflectanceloss from source particles, a tremendous issue in earlier laser plasma sources, has been reduced by a factor of over 1 million through the use of cluster jet targets. While additional improvements are needed in this area, significant progress continues to be made, as discussed below.

II. Cluster Jet EUV Source Overview

The cluster jet source employs a stream of high-density van der Waals clusters of inert gas such as xenon, produced by isentropic expansion of the gas from high pressure through a supersonic nozzle into vacuum. The clusters are irradiated with a focused laser, providing a medium of dispersed solid-density targets that achieves excellent energy extraction (>90%) from the focused drive laser to produce the heated plasma. Due to 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. Early CE measurements demonstrated that this source is nearly as efficientat 13.5 nm as sources based on Au targets, converting 0.6 % of the drive laser pulse energy into in-band EUV energy. At the same time, the reflectance of multilayer-coated condenser optics placed near the source was reduced by 10 % after 10^8 plasma pulses, a factor of >100,000 improvement over earlier Au targets.

Pulsed nozzles have been used to develop early, low-repetition-rate cluster jet sources, but continuous nozzles with Xe recycling will be required for the >1000 Hz laser repetition rates employed in commercial systems. Thus, it is important not only that the cluster jet source achieve the highest possible conversion efficiency from laser energy to in-band EUV energy, but that it simultaneously minimize the mass flow rate of Xe. Increasing conversion efficiency is obviously desirable because it results in increased throughput for a given incident average laser power. Reducing Xe mass flow rate is desirable because it results in a smaller required vacuum pumping rate for a given partial pressure of highly EUV-attenuating Xe background vapor. Since an earlier publication[1], we have reduced the steady-state Xe mass flow rates by a factor of 16 while increasing the conversion efficiency by ~30 %. This has significantly simplified the vacuum pumping and Xe gas recycling requirements for the prototype source subsystem being developed now to meet commercial EUV power specifications. Simultaneously, these nozzles can be made to emit and deliver more EUV power than their predecessors.

III. Cluster Jet EUV Radiation Properties

IIIa. Cluster jet plasma spectroscopy

Spectroscopic characterization of the cluster jet plasma emission is performed with a high-throughput EUV/Soft X-Ray monochromator, shown schematically in Fig. 1 and described previously[7]. Spectra are recorded by averaging 10 laser plasma pulses per wavelength increment with a filtered silicon photodiode (IRD AXUV 100) and scanning the monochromator grating over the spectral region of interest. The resulting 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 a typical Xe cluster jet source. As can be seen, the emission shows an intense unresolved transition array centered at 11 nm as well as several absorption features between 13 - 15 nm. These have been identified previously by Carroll and O'Sullivan[8] who have shown that the broad, intense feature near 11 nm is the result of 4d-4f transitions in Xe VII - Xe XII ion stages. The weak absorption dips near 13 nm correspond to various transitions in Xe VI, VII, and VIII.

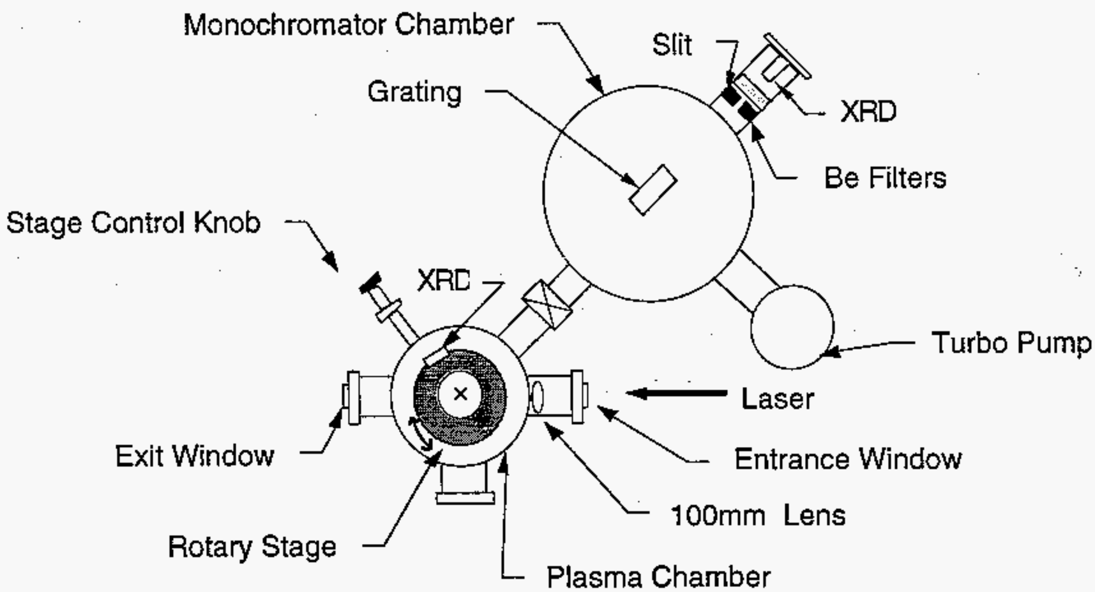

Figure 1. Schematic diagram of the cluster jet laser plasma source, EUV monochromator, and nozzle material deposition fixture.

The most significant aspect of the spectrum shown in Fig. 2 is that the cluster jet emission intensity near 10.9 nm is a factor of 8 times greater than that at 13.4 nm. Current EUVL optical systems are optimized at wavelengths between 13-13.5 nm, corresponding to the region of maximum reflectanceof Mo/Si multilayer mirrors. It is clear from Fig. 2 that a significant increase in EUVL throughput may be realized for systems operating near 11 nm instead. This may be possible if Mo/Be multilayer technology can be developed to systematically and uniformly obtain reflectancevalues ≥ 65 % near 11.4 nm

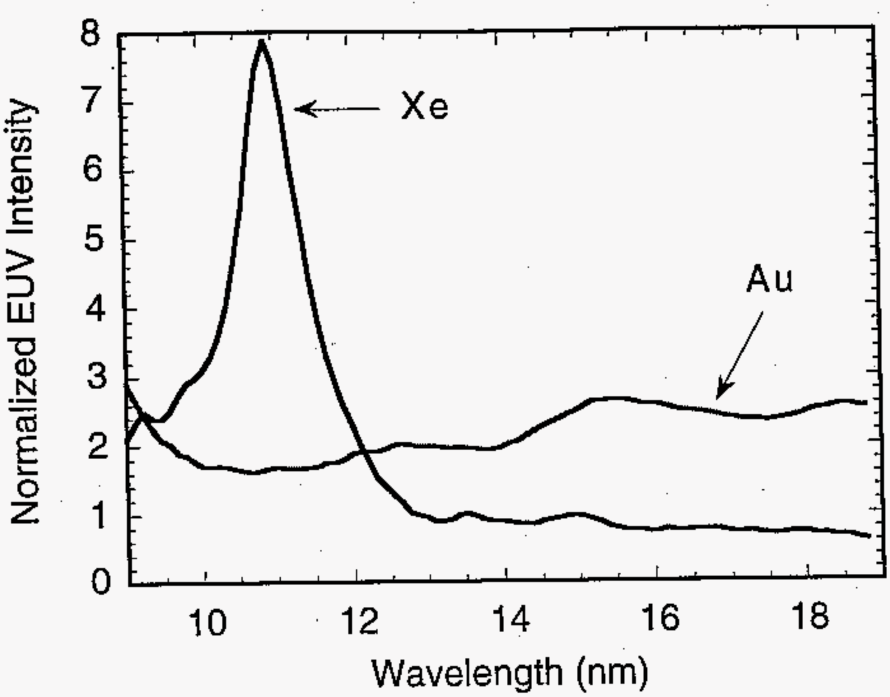

Figure 2. Xe cluster jet and solid Au laser plasma emission spectra.

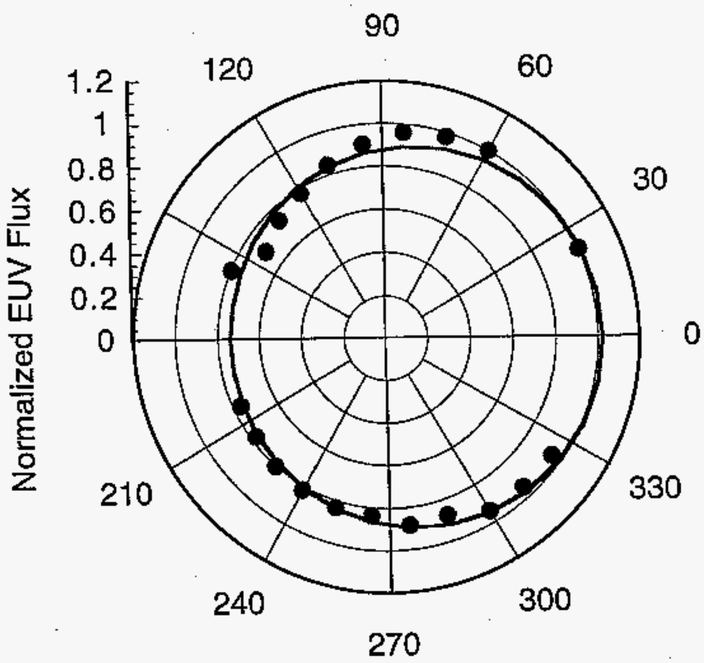

Figure 3 Angular distribution of cluster jet plasma EUV emission. Line is a best fit to the experimental points, having the form $F(\theta) = 0.13 + 0.85*\cos(\theta)$.

as has been achieved near 13 nm with Mo/Si. Since maximum reflectance values of 69 % have already been reported in early Mo/Be multilayer demonstrations[9], such development is likely to be fruitful.

IIIb. Angular distributions of Xe plasma emission

To establish the most efficientrange 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 is made with a filtered silicon XUV photodiode detector mounted on a rotating platform. The detector is 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 3 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 $F(\theta) = 0.88 + 0.13 \cos\theta$, a form that is quite differentthan that 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 due to the fact that the cluster jet beam opacity is finite, in contrast to the infinite opacity of the solid target. Thus, it may be possible to design condensers that collect cluster jet source radiation over a larger total solid angle than is possible for sources based on solid targets.

IIIc. EUV source emission images

For efficient light collection and illumination, it is important that the brightness or radiance of the source (i.e. the power per unit area per unit solid angle) be maximized. It is clear from Sec. IIIb that the source fills 4π steradians almost uniformly. To establish the emission area of the source, and thus its brightness, EUV images of the cluster jet plasma emission are obtained with a pinhole camera, filtered to record only in the spectral region between ~70 - 110 eV. The camera is oriented to view the plasma at a 45° angle with respect to the laser propagation axis. Its magnification is 4.93 and the resulting images are recorded with a back-thinned CCD imaging detector. Fig. 4 shows a representative image and corresponding intensity profiles integrated over 10 pulses from a plasma produced by 0.36 J laser pulses focused near the exit orifice of a supersonic Xe nozzle. The profile projected along the laser propagation axis has been corrected to account for the 45° camera viewing angle. As can be seen, the FWHM source size in the laser propagation and transverse directions is 181 and 83 μm, respectively. The source is brighter near the leading edge of the laser-jet interaction volume and is larger along the laser propagation direction than transverse to it. Under sub-optimal nozzle conditions, the plasma image elongates greatly along the laser axis and the image becomes a non-uniform collection of uncoalesced bright regions. Under these conditions, the total integrated plasma flux is larger than under optimal conditions, but the brightness is lower due to the larger size of the radiating volume.

In order to establish the absolute EUV pulse energy emitted per laser pulse, integrated over 2π steradians and a 2.5% spectral bandwidth, we use a detector spectrally filtered to restrict its sensitivity to a narrow region centered about 13.4 nm. Under the conditions used to produce the image shown in Fig. 4, the integrated yield of 13.4 nm energy is 2.2 ± 0.35 mJ, corresponding to a CE of 0.62 ± 0.1 %. These values increase to 3.4 ± 0.54 mJ and 0.95 ± 0.15 % when the laser is focused closer to the nozzle exit plane. The source brightness under these conditions, based on the measured angular and spatial distributions discussed above, is 4.6 - 7.1 J/ cm^2-sterad per pulse. The corresponding brightness values at 11.4 nm, near the peak spectral reflectanceof Mo/Be mirrors, are approximately four times greater at 2.4 % and 3.8 %, based on the source power spectral dependence shown in Fig. 2. These brightness values are obtained by performing the angular integration over the "forward" 2π steradian emission direction only, since most condenser schemes consider only this hemisphere. Brightness values averaged over the entire 4π steradian emission sphere will be somewhat lower due to the weaker emission in the other hemisphere.

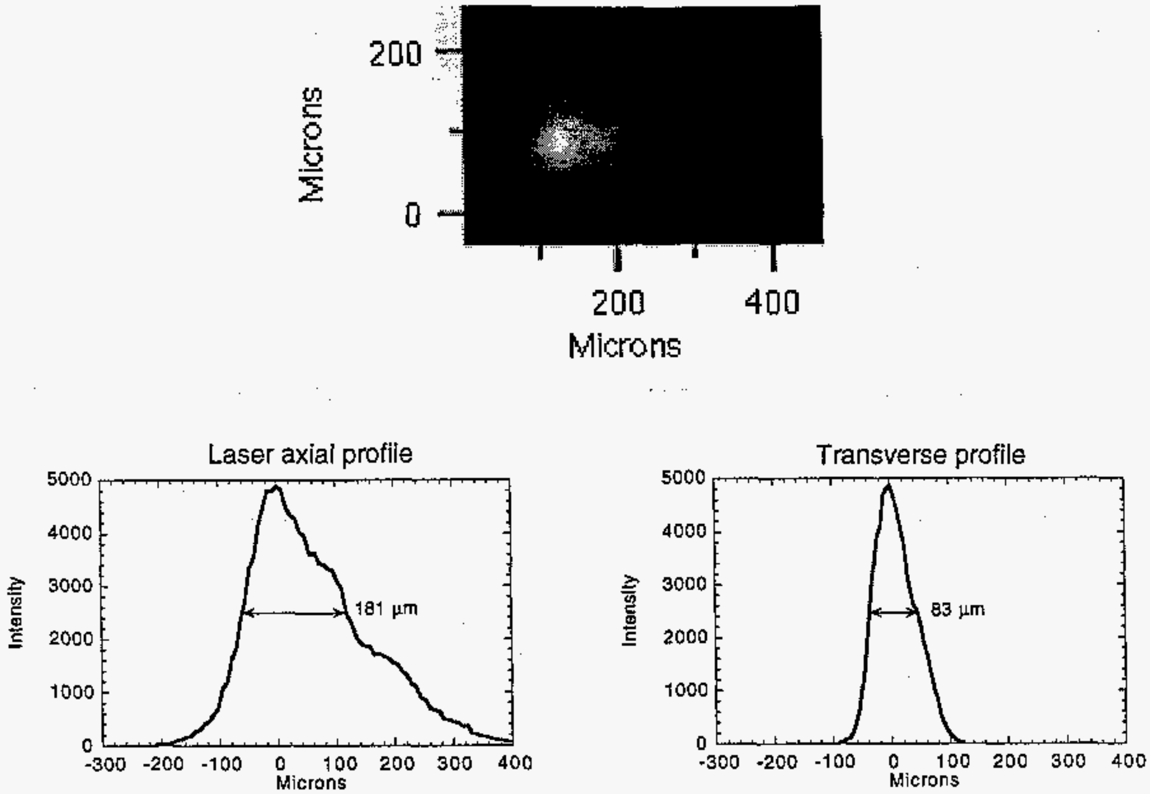

Figure 4. EUV image of source emission (top) and the associated horizontal (laser axis) and vertical (transverse to laser axis) profiles (bottom). The laser axial profile has been corrected for the 45° camera viewing angle.

IV. Nozzle erosion studies

As mentioned earlier, the rate of multilayer mirror reflectance loss from eroded nozzle material must be decreased to increase condenser lifetime and reliability. We have investigated a number of methods to reduce nozzle erosion and subsequent deposition on nearby condenser surfaces. Experiments are carried out by exposing modified nozzles to approximately 10^7 full-power laser plasma pulses under nominal laser and nozzle stagnation conditions. Laser focus is held fixed at a distance of 1.5 mm from the end of each nozzle. During exposure, 2.54 cm diameter silicon deposition substrates ("witness plates") are positioned 12.7 cm from the laser plasma to collect any nozzle or other material eroded by the plasma. Each silicon substrate is oriented so that its projected surface normal passes approximately through the plasma. Upon completion of each exposure experiment, the silicon witness plate was removed and the deposited film analyzed by sputter depth profiling with Auger Electron Spectroscopy to establish film composition and depth.

The first experiment was performed to establish the baseline deposition rate for the standard nozzle configuration, similar to that used in Ref. 1. Three subsequent experiments (Trials M3, M51, and M103) were performed under conditions designed to reduce the erosion and deposition of nozzle material. In all cases, the deposited films appeared smooth and unstructured when examined with scanning Auger electron microscopy. The results of the sputter depth profiling analysis for the four experiments are graphed in Fig. 5, which shows the atomic fraction of deposited nozzle material measured as a function of depth. The integrated areas under the depth profiles of figure 5 show that the amount of deposited nozzle material is reduced by 25% in trial M3 compared to the baseline value (curve B). Trial M51 shows a more effectivereduction in which the integrated amount of deposition is decreased by a factor of 4.6. Trial M103 is the most successful, revealing a factor of 14 reduction. It is important to note that the methods employed in Trials M3, M51, and M103 achieve reduced nozzle deposition rates without any attenuation or obscuration of the EUV beam. It is likely that further reductions in deposition can be achieved through the selective use of techniques developed to minimize deposition from solid targets, although these may result in a slight decrease in EUV flux.

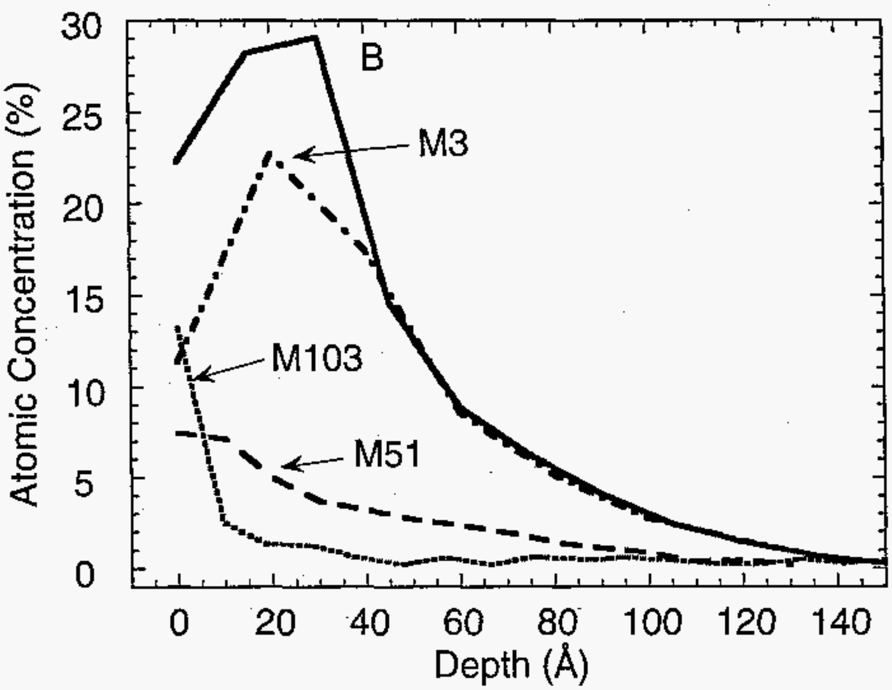

Figure 5. Auger depth profiles of films of eroded nozzle material deposited on Si substrates placed 12.7 cm from the plasma source after 1x 10^7 plasma pulses. See text for details.

Figure 6 summarizes the increases in condenser reflectance lifetime achieved since the earliest implementation of Au laser plasma source targets for EUV lithography. Lifetime is expressed as the time in plasma pulses required for the reflectance of a plasma-facing multilayer mirror placed 12 cm from the source to be reduced by 10%. All but the latest two data points are based on actual measurements of the time rate of change of reflectancefor multilayer mirrors exposed to the various laser plasma sources. The last two data points are based on extrapolations of the reflectancelifetime of the mirror exposed to the original cluster jet source. The extrapolations were performed by scaling this lifetime by the reduced material deposition rates measured in Trials M51 and M103. As can be seen, mirror lifetime has been increased by a factor of ~1 million since 1991.

III. Summary and Conclusions

The EUV emission properties of Xe cluster jet laser plasmas have been characterized and methods to reduce the associated erosion and deposition of nozzle material on nearby plasma-facing multilayer mirrors investigated. The spectroscopy of the source emission is dominated by a broad, intense feature centered at 10.9 nm. Under appropriate conditions, the CE of the source is found to be 0.62 - 0.95 % at 13.4 nm and approximately four times greater at 11.4 nm, wavelengths suitable for Mo/Si and Mo/Be multilayer mirrors, respectively. Emission angular distributions are found to be much more uniformly distributed over 4π steradians than those measured previously for solid targets, and are well described by the expression $F(\theta) = 0.88 + 0.13 \cos\theta$. EUV images of the source reveal that the FWHM size of the emission volume is

83 µm transverse to the laser and 181 µm along the laser propagation direction. To increase the lifetime of plasma-facing multilayer mirrors, methods to reduce the erosion and subsequent deposition of nozzle material have been developed, resulting in improvements of up to a factor of 14 over earlier work. Based on these improvements, plasma-facing condenser mirror lifetimes have been increased by a factor of 10^6 since 1991.

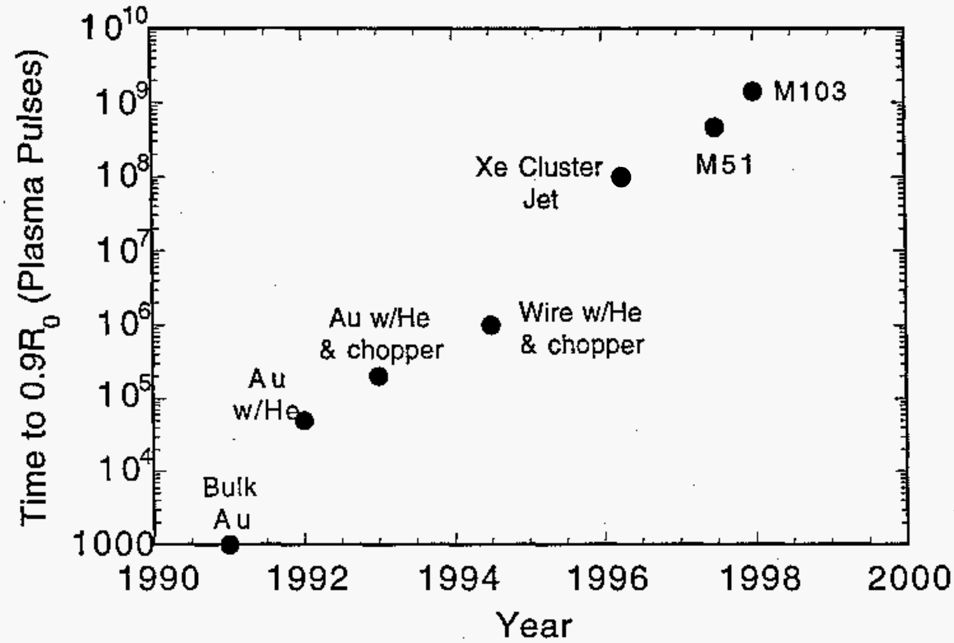

Figure 6. Progress on EUVL condenser mirror lifetimes, expressed as the number of plasma pulses required to reduce the original mirror reflectance by 10%.

Acknowledgments

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