Characterization and control of laser plasma flux parameters for soft-x-ray projection lithography

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Laser plasmas are intrinsically an attractive soft-x-ray source for projection lithography. Compact, flexible, and small enough to be dedicated to a single installation, they offer an alternative to costly multi-installation synchrotron sources. For laser plasmas to provide ideal sources of soft x rays for projection lithography, their properties must be tuned to optimize several critical parameters. High x-ray conversion in the spectral band relevant to projection lithography is obviously required and has already received the attention of several studies. However, other features, such as the spectral content and direction of the x-ray emission, the plasma and particulate emission, the technology of the target, and efficient laser design, must also be optimized. No systematic study of all these features specifically for projection lithography has yet been made. It is our purpose to optimize these parameters in a coordinated approach, which leads to the design of a source that satisfies all the demanding requirements of an operating lithographic installation. We make an initial investigation of the plasma and particle emission of plasmas that have previously been shown to be good x-ray converters to the 13-nm band. The importance of the results reported may well force new approaches to the design of laser plasma soft-x-ray sources for projection lithography.

1. Introduction

In current projection x-ray lithography schemes,[1-3] the use of a bright soft-x-ray source operating in the wavelength region of 13 nm, where efficient high reflective mirrors have already been demonstrated, is envisaged. Several possible candidate sources are currently under consideration, including compact synchrotrons,[4] free-electron lasers,[5] laser plasmas,[6] and various types of discharge device.[7] There is much interest in the concept of using bright laser plasma x-ray sources for soft-x-ray projection lithography. The use of a laser plasma instead of a compact synchrotron offers the advantages of flexibility, cost, single-source dedication, and operational convenience. Compared with other possible pulsed x-ray sources, such as free-electron lasers and discharge devices, laser plasma sources are fairly well developed and understood and should be able to provide the required soft-x-ray fluxes. Laser plasma sources, therefore, in principle, present a low-risk path toward a compact, low-cost, soft-x-ray source suitable for a single-stepper production facility for advanced integrated circuits.

Although laser plasmas have been under intense investigation for many years, the investigation being driven by their application to such projects as laser fusion and coherent x-ray laser generation, only limited studies have been made with sufficient spectral resolution in an operating regime approaching that which might be optimum for soft-x-ray projection lithography.[6,8-10] All these studies have been made with available, generally commercial, laser systems and were performed with simple planar solid-material targets. Although recent studies of the soft-x-ray emission spectra from plasmas produced under these conditions have estimated conversion efficiencies of the laser light into x-ray emission within the bandwidth of typical normal-incidence x-ray mirrors to be in the 1% range,[10] to our knowledge no systematic study has yet been done to optimize all the parameters of a laser plasma specifically for the high-repetition-rate, long-duty-cycle operational environment of a high-throughput wafer production facility.

Several unique and, in some respects, mutually conflicting characteristics are required of a laser plasma ideally configured as an x-ray source for

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projection lithography. Here we briefly examine the most important of these characteristics.

A. X-Ray Conversion

The laser plasma source must display high conversion efficiency to x rays in the region of 13 nm within a narrow bandwidth. This requirement is set, at the present time, by the availability of high reflective normal-incidence x-ray mirror coatings.[11]

Because all projection lithography designs utilize a large number of reflective surfaces in series (usually ~ 7), the R^7 dependence of the system transmittance will strongly influence the choice of operating wavelength. This is currently restricted to a narrow spectral region near 13 nm, where multilayer Mo–Si mirrors can be fabricated to near their theoretical reflectivities ($R \sim 70\%$).[12] Other characteristics of laser plasma x-ray emission not usually found in these sources would also be desirable. Since only a small spectral bandwidth of radiation is used for projection lithography, one would ideally want the source to be spectrally narrow, thereby limiting the amount of unused x-ray radiation that will be absorbed by the first surface mirror. The absorbed flux could be so high as to cause degradation or damage to this mirror. The presence of this unwanted flux would suggest ideally the creation of a predominantly x-ray line emission in the plasma. Unfortunately, the spectrum of laser plasma emission usually comprises a broad continuum of Planckian radiation from free-bound plasma collisions, on which a host of emission lines at many wavelengths from many ionic transitions are superimposed.[13] Another aspect relates to the geometric match between the emission direction of the x-ray emission and the numerical aperture (NA) of the first collector mirror (typically NA $\sim$ 0.15).[14] An ideal source would be one in which the x rays are emitted from the laser plasma with an angular distribution corresponding to this aperture, thereby limiting the amount of unused x-ray emission. X-ray emission from laser plasmas created with planar targets is usually conical in nature, but with a solid angle much greater than this aperture would require.[15] Last, since there are no ultrafast time-dependent characteristics required of projection lithography sources, ideally long-duration emitting plasmas would be preferable, especially if this meant that an increase in the x-ray conversion efficiency would be gained. Most types of laser plasma designed for x-ray generation have a very short duration emission, typically a few nanoseconds at most (these are required for such applications as laser fusion and x-ray laser generation). Intrinsically, since a laser plasma is inertially confined, its x-ray emission lifetime will be limited, but times larger than these few nanoseconds would be beneficial. Thus the greater the degree to which all these parameters can be manipulated to provide efficiently generated useful 13-nm x-ray emission, the lower the output power requirements, complexity, and cost of the laser will be. Given that this source must operate for long periods of time without major maintenance, improved reliability will result.

B. Plasma and Particulate Emission

A laser plasma source for projection lithography must not contaminate the laser focusing optics and the x-ray collecting optics. It is unreasonable and would be too costly to assume that these optics can be replaced after short periods of operation. Laser plasma x-ray sources inherently produce ballistic particles emanating from the plasma in all directions. The magnitude, size, and velocity of these particles is, of course, dependent on the target and the irradiation conditions. All this flying particulate emission is potentially hazardous to these optical elements, either in its ability to degrade their surface quality or in the progressive degradation of their performance that is due to overcoating with target material. Although it has long been recognized that plasma debris is a potential problem for high-speed lithography,[16] it has not been the strong focus of previous investigations of laser plasmas. Single-shot applications, such as laser fusion and x-ray lasers, are not impaired by this debris problem. Laser ablation material-coating studies actually depend on such particulate emission but are done in a laser intensity regime that is far removed from that in which significant x rays are generated.[17] However, to our knowledge no systematic studies have so far been made in which the specific requirements relative to soft-x-ray projection lithography are addressed. No attempts have been made to minimize the particulate emission while at the same time ensuring that strong x-ray emission is maintained at 13 nm. In addition, for lithography applications it may well be necessary to devise techniques and devices that actually inhibit or capture the flow of these particles. Little work has been reported so far in this domain.

C. Target System

A third requirement of a laser plasma x-ray source for projection lithography is an inexpensive, continuously sequencing target system. Current designs for a stand-alone projection lithography installation call for a laser plasma source operating at a frequency in the vicinity of 1000 Hz.[18] Assuming the need for nonstop operation for an 8-h operating period and the requirement of a fresh target per shot implies a noninterfering shot sequence of more than 2×10^7 targets. The design of a system with such a capability is, of necessity, dependent on knowledge of the optimum target design and irradiation conditions. Although workers at Sandia National Laboratories were the first to use a high-speed tape target system specifically for laser plasma soft-x-ray projection lithography experiments,[19] a target system suitable for a commercial projection lithography installation is far from being developed.

D. High-Repetition-Rate Laser

A fourth technological requirement for a high-repetition-rate x-ray source for projection lithography is, of course, the need for a suitable laser system to produce the plasma. The specification of its ultimate output characteristics will have to await the results of the experimentation referred to above; however, some comments can be made on the required features of this laser system. The strict constraints on long-term high-repetition-rate operation with high reliability at a minimal operating cost will strongly limit the choice of laser candidates. Factors such as laser wavelength and pulse shape will probably also play a role. At the present time, the two leading candidates would appear to be high-repetition-rate, diode-pumped, Nd:YAG lasers operating at their fundamental wavelength (1064 nm) or their second harmonic (532 nm), or high-repetition-rate, short-wavelength (248-nm) KrF excimer lasers. Were one forced to specify a suitable laser system at the present time on the assumption of the conversion efficiencies to soft x rays so far achieved at 13 nm, it would be at or beyond the limits of these two technologies. Clearly, improvements in target design, conversion efficiency, and satisfactory solutions to the debris issue could, in principle, bring the required specifications closer to or within the limits of present technology.

In this paper we begin to address the issues raised above. It is clear that no one issue can be solved without considering its relationship to the others. It is therefore our intent, ultimately, to address all these issues in a self-consistent manner. Without such a systematic approach, the choice of a laser plasma as a suitable source for soft-x-ray projection lithography might be inadvertently bypassed in favor of some competing technology, such as synchrotrons, and the overall scheme of projection lithography changed as a consequence. In our first studies of these problems, reported here, we concentrate on defining some of the principal limitations of laser plasmas, *as they are currently used,* to the requirements of a projection lithography source. In particular, we report some novel characterizations of the particulate emission from these laser plasmas and make some logical extrapolations of these measurements to the conditions necessary for a lithography installation. Although the study is preliminary in nature, several important conclusions can be safely drawn from this work. These are summarized in Section 6.

2. Experimental Conditions

The emphasis of the present study was on making an initial characterization of the particulate emission from laser plasmas similar to those that have been recently used to demonstrate high soft-x-ray conversion for soft-x-ray projection lithography. These early studies are restricted to measurements made with solid-state lasers. The conditions closely resemble the conditions used in current x-ray conversion measurements at Lawrence Livermore National Laboratory. The particulate emission has been measured by several techniques. Clear demarcations have been drawn between different types of particulate emission. In this section we describe the conditions under which this particulate emission was characterized.

Two laser target installations have been established at the Laser Plasma Laboratory at the Center for Research in Electro-Optics and Lasers for the purpose of investigating those properties of laser plasmas of importance to soft-x-ray projection lithography. The principal features of these installations are shown schematically in Fig. 1. The first facility, which is shown in Fig. 1(a), utilizes a commercial Q-switched oscillator–amplifier Nd:YAG laser that produces pulses at up to repetition rate 10 Hz with ~ 750 mJ of energy and ~ 10 ns in duration.[20] The laser is multimode with a beam divergence of 6×10^{-4} rad. The laser operates at a wavelength of 1064 nm or, with second-harmonic conversion, can provide energies of as much as 400 mJ at 532 nm. Plasmas are produced from solid targets by the radiation of this laser focused with an $f = 12$-cm lens into a target chamber with a base vacuum of 2×10^{-4} Torr. The laser intensity in the target plane of this laser was accurately characterized by infrared photography of the equivalent target plane intensity distribution produced by a 50-cm focal-length lens with an optical wedged image rattle plate, as shown in the layout illustrated in Fig. 2(a). A typical isodensity contour plot of the radiation distribution in the equivalent target plane is shown in Fig. 2(b). The minimum FWHM spot diameter of the radiation distribution in the chamber of Fig. 1(a) is ~ 80 μm. All the experiments reported with this system were performed with

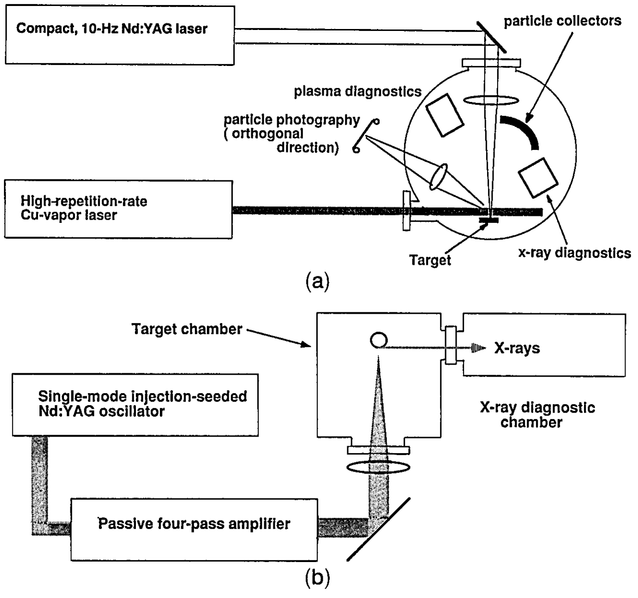


Fig. 1. Two experimental laser target facilities for laser plasma studies directed at soft-x-ray projection lithography. (a) Facility equipped for the analysis of the particulate emission from plasmas produced with a commercial Nd:YAG Q-switched laser system. (b) Target facility built around an oscillator–amplifier Nd laser system with well-controlled temporal and spatial beam characteristics.

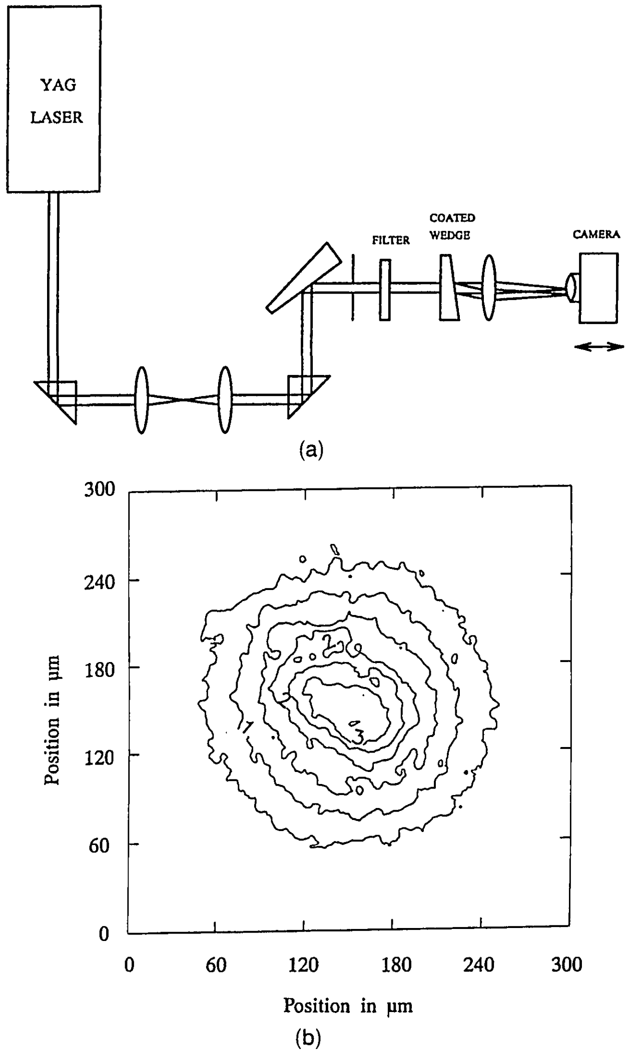


Fig. 2. Measurement of the laser beam focal spot distribution for the laser target facility shown in Fig. 1(a). (a) Schematic of the technique used to measure the focal plane distribution. (b) Isodensity contour plot of the distribution at best focus. The isodensity contours range between 0.5 and 3.0.

a rotating-disk target system, permitting a fresh target region to be presented in the focal region for each shot. The rotation of this target could be automated for multishot operation. The target was adjusted to this target position on each shot by maximizing the hard-x-ray emission (that greater than 1 keV) emanating from the target. This emission was monitored with a p-i-n x-ray diode in combination with a 25-μm-thick Al filter. This target facility has several methods of assaying the plasma emissions from the target. The velocity and the relative number of charged particles are measured with Faraday cup charge collectors. Neutral atomic particulate emission and the charged particles are captured on acetate collectors, and large clusters of material, so-called "hot rocks," are analyzed with the use of a high-repetition-rate (14-kHz) Cu-vapor laser.[21] These diagnostics are discussed in detail below.

The second laser target installation used for these studies employed a novel laser configuration, which is shown in Fig. 1(b). This laser was designed specifically to provide a uniform, well-characterized intensity distribution on target. This intensity distribution should help ensure the production of an x-ray source with a uniform spatial distribution of x-ray emission. This has recently been shown to be an important requirement of a projection lithography x-ray source. In most published optical schemes for the mask illumination, a ring-field image of this distribution, created by a multilens configuration of the condenser optics, is raster scanned across the reflection mask. Uniformity of the x-ray distribution of the x-ray target is therefore an important requirement for uniform illumination of the mask. The laser system used in this installation, which is shown schematically in Fig. 3, attempts to ensure this. When a single-longitudinal-mode Gaussian beam distribution in a smoothly varying form Gaussian laser pulse is generated, a well-characterized laser intensity distribution is produced in the target plane. This distribution is achieved through the development of a single-mode injection-seeded Q-switched oscillator with a diode-pumped single-mode Nd:YAG oscillator,[22] producing a stable single-mode output. The 10-ns-duration, ~10-mJ pulse from this laser is then amplified in an imaged relayed amplifier system. The first part of this amplifier system employs a novel passive four-pass amplifier design. This type of amplifier has been investigated by Andreev *et al.*[23] and also formed the subject of a detailed study by Hunt.[24] The present design is shown in Fig. 3. The oscillator output is fed into this amplifier system through a polarizer and a Faraday rotator. The pulse then makes four successive passes through a 460-mm-long, 16-mm-diameter, Nd:glass amplifier and a 3-m-long, one-to-one vacuum spatial filter. The overall amplification is ~400, with a final output energy of 2.7 J. The pulse duration and the uniform beam quality are preserved through this amplification process. The output of this laser is focused with a 100-mm focal-length lens onto a target chamber with a vacuum base pressure of 2×10^{-5} Torr. The target assembly used in this facility is a rotating rod assembly. This system permits the angular depen-

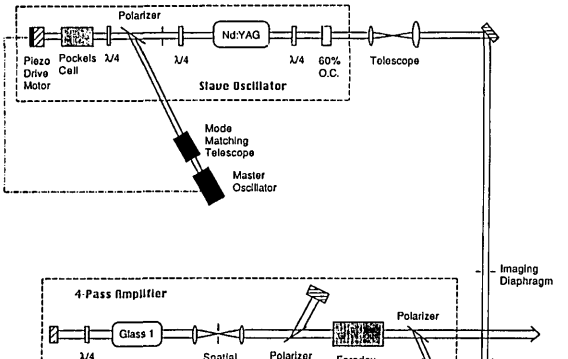


Fig. 3. Injection-seeded Nd:YAG oscillator with a passive four-pass Nd:glass amplifier. O.C., optical condenser.

dences of plasma emissions to be easily analyzed. Attached to the target chamber is a large diagnostic chamber for x-ray instrumentation. In the present studies, the only diagnostic used is fast planar soft-x-ray photodiodes filtered with the use of a multilayer mirror to analyze the x-ray emission at 13 nm from the plasma.

3. Characterization of Particulate Emission

The particulate emission emanating from a laser plasma created off a solid target has several forms. These forms and their relative flux change as a function of time during and after the interaction. Three specific forms of particulate matter can at present be identified. These are shown schematically in Fig. 4. During the interaction of the laser light with the plasma, highly stripped, energetic ions are formed by collisional ionization resulting from inverse bremsstrahlung absorption of the laser light by the plasma, the primary absorption mechanism in this interaction regime. These ions stream ballistically from the plasma region with velocities in the range 10^6–10^7 cm/s. Their total number can be quite large ($> 10^{16}$ ions), which accounts for the majority of the mass ablated during the laser plasma interaction. This absorption mechanism and electron thermal transport of the absorbed energy will ablate several hundred nanometers of the target during this process. Immediately after the laser pulse, the plasma cools as further ablation of material occurs from the target. Thus a number of neutral atoms are ablated at this time. In addition, neutral atomic flux may also be generated on the periphery of the plasma during the laser plasma interaction and as a consequence of electron-ion recombination in the plasma. At still later times, after the interaction of the plasma with the target, hot clumps or clusters of target material are boiled off of the target. This occurs within a crater that is formed in the target surface by the interaction. The three-dimensional nature of this crater creates turbulent flow of the molten matter from the crater. The form of this matter, as far as the size, velocity, and relative number of clusters are concerned, is probably dependent on the form of the crater made in the target and on the material characteristics of the target used.

In the present studies the clusters or hot rocks were studied optically. Early measurements have shown that these clusters have sufficient temperatures such that they emit blackbody emission in the visible part of the spectrum and can be photographed in flight. Their trajectory then appears as a streak of light, generally of decreasing luminosity as the cluster cools. This approach, however, provides no information on size or velocity of the clusters. We have used a photographic approach in which the clusters are illuminated with a rapid sequence of bright visible laser pulses. The light scattered from the clusters then provides an indication of their size and, more importantly, an instantaneous measure of their velocity during their trajectory. We are therefore able to estimate their momentum and impulse. The latter information is vital to estimating the potential these particles have for damaging the x-ray and visible optical systems situated in their path.

The setup used for these studies is shown in Fig. 5. Most measurements have been made so far on Sn targets. The plasmas are produced on a solid rotating wheel target assembly irradiated at 45° by the Nd:YAG laser shown in Fig. 1. The particles emanating from the target are illuminated across a 25-mm-diameter field running parallel to and immediately in front of the target by the output of a 511-nm Cu-vapor laser producing 50-ns pulses with an individual energy of 3 mJ at a frequency of 14 kHz. The clusters passing through this field are then illuminated every 71.4 ms. They are photographed in flight by a film camera located in a direction orthogonal to the plane containing the Nd:YAG and Cu-vapor laser beams. A typical photograph of the particles emanating from a Sn laser plasma crater taken by this method is shown in Fig. 6. The trajectories of all the particles in the illumination field of the Cu-vapor laser are visible as lines of bright dots, each

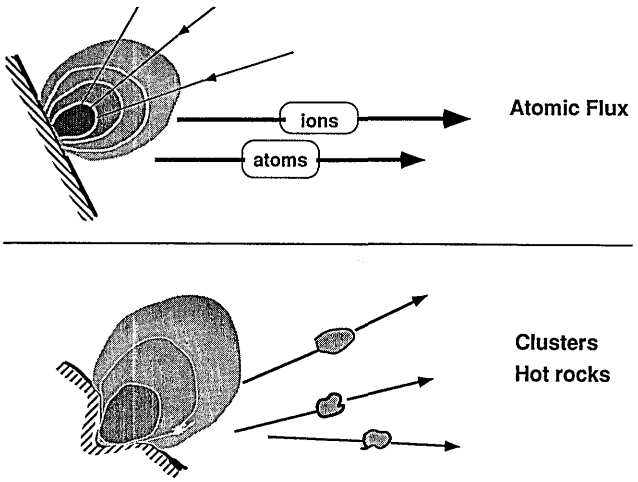


Fig. 4. Plasma and particulate matter emanating from a laser plasma produced from a solid target.

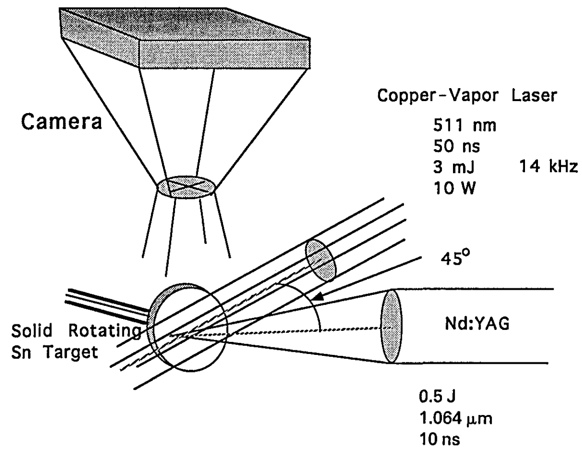


Fig. 5. Experimental arrangement used to estimate the velocity and the size of clusters emanating from laser plasmas.

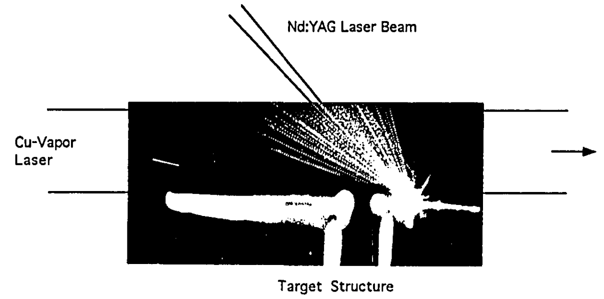


Fig. 6. Photograph of high-repetition-rate (14-kHz) pulses of a 511-nm-wavelength, Cu-vapor laser light scattered from clusters emanating from a Sn laser plasma.

dot resulting from the particle being illuminated by the Cu-vapor laser. Measurements of the size and the separation of the dots in each trajectory then provide a measure of the mass and the velocity of each particle. From these data the angular distribution and total mass and the energy and impulse resident in this form of particulate emission can be estimated. The typical angular distribution of the velocities clusters emanating from Sn target craters is shown in Fig. 7. As can be seen, the velocities of these particles range over nearly an order of magnitude, from 200 to 1000 cm/s. Particles with velocities as high as 2500 cm/s have been observed with this technique. The sizes of these particles range from less than 10 to greater than 200 mm. The latter size is comparable with the spot size of the irradiating laser and the soft-x-ray emitting zone. Thus these particles have energies of 1×10^{-3} to 4×10^{-2} gm cm^2/s^2 and specific impulses per unit area in the range 3–100 mJ/cm s. This is sufficient to cause cold particle cratering of most materials of the type used to construct visible and x-ray optical components and is capable of puncturing any thin-film x-ray filters used in the 13-nm region.

Although a full parametric study has yet to be made with this diagnostic, one significant feature is apparent for the plasmas created in this study. This is illustrated in Fig. 8, which shows the number of clusters created across a given field from an Sn target as a function of the number of shots incident upon the same position of the target. In this case we see that for the laser irradiation and the target conditions used in this study, no particles detectable with this technique were observed for clean target conditions. As discussed below, this observation has a significant impact on possible high-repetition-rate soft-x-ray source schemes for projection lithography. Another observation from Fig. 8 is the fact that the number of clusters emanating from the target increases with the number of shots on the same target position. This implies that the cluster emission increases with the depth of the crater formed in the solid target by progressive laser irradiation. With successive shots on the same target position, the walls of the crater will progressively steepen. Laser light absorbed on the wall of this crater will increasingly boil off more material. This effect also has serious implications for the use of solid targets in an x-ray source for projection lithography and is discussed in Section 5.

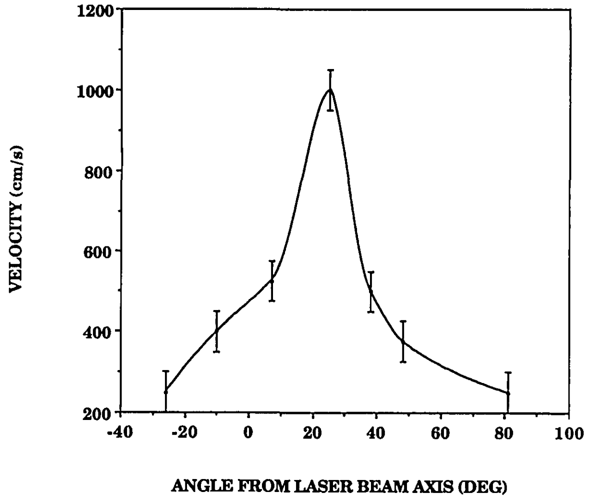


Fig. 7. Angular distribution of the velocity of cluster emission from a Sn laser plasma target created from a solid target after a crater had been produced by ~40 shots.

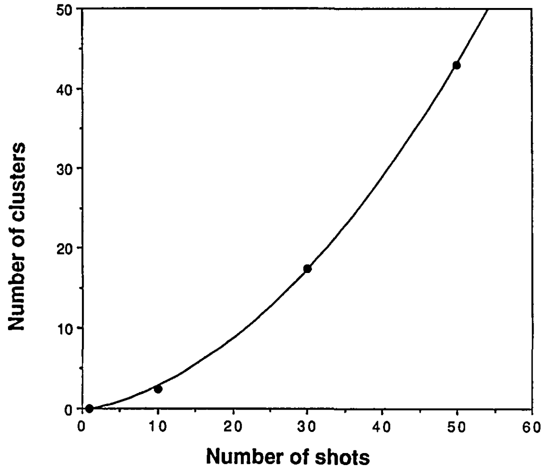


Fig. 8. Increase in the cluster emission per shot as a function of the number of shots irradiating a single point on the target.

4. Measurement of Atomic Flux Emission

Atomic and ionic flux measurements from Sn targets with the laser target facility illustrated in Fig. 1(a) were made primarily with the technique that captured the angular distribution of this flux on acetate or glass substrates. This is illustrated in Fig. 9(a). The 3 cm × 5 cm acetate collector was positioned in an arc around the target, as shown in Fig. 9(a), in such a manner as to collect all the particulate emission from the target. The acetate was positioned ~2.5 cm from the target. Typically the debris from many shots were accumulated to acquire sufficient deposition of target mass on the collector. To avoid the generation of clusters, a virgin target surface was used for each shot. The latter was facilitated by the incorporation of an automatic rotational drive to the target wheel assembly shown in Fig. 1(a). Quantitative data were extracted from the recorded

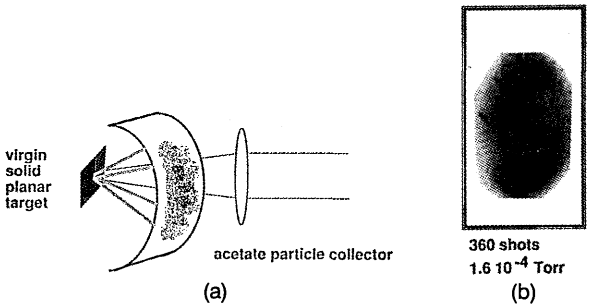


Fig. 9. Experimental approach to measuring atomic flux from laser plasma targets: (a) use of collector plates, (b) typical mass deposit on curved collector plate.

deposition by densitometering of the distribution. Then, from known optical opacity-thickness characteristics of the target material, the thickness or mass distribution of the deposited material was determined on the assumption that the target material was sputtered uniformly. The angular distribution of the atomic flux emanating from the target can be obtained from these data. Measurements were made on Sn, Fe, and Au targets. For Sn targets, the total mass deposited on the collector per shot was ~1 mg. This implies that, for an irradiation spot diameter of ~200 μm, the thickness of material ablated away as atomic material (in the absence of clusters and without the formation of a crater) was ~3 μm. The plasma ablation depth during the laser irradiation is only ~0.3 μm; this implies that ~10 times more mass is ablated from the target after the laser pulse as neutral or slightly ionized matter. An example of data obtained on an acetate collector is shown in Fig. 9(b). It can be seen that, despite the fact that a planar solid target is used, the atomic flux has a strong angular distribution. For Sn targets, the peak atomic flux is $\sim 2 \times 10^{-9}$ g/sr/pulse. The angular distributions of the mass deposition per shot about an axis normal to the target surface for different target materials is shown in Fig. 10. The mass deposition for Fe is significantly lower than that for Au or Sn by a factor of ~3. All these data were obtained with a background pressure in the target chamber of $\sim 1.5 \times 10^{-4}$ Torr. Under this condition, the particles are ballistic. They have a negligible chance of undergoing collisions with background gas molecules (mostly N_2). The implications of this flux for possible x-ray sources for projection lithography are discussed in Section 5. One approach commonly suggested for reducing the impact of this flux on optical components is the use of a background gas of He with a pressure high enough to impede the atomic flux particles collisionally, yet of a pressure low enough to ensure minimal opacity to the soft-x-ray radiation. These conditions are met for the present irradiation conditions with a He background pressure of ~0.2 Torr. Atomic flux collector measurements were made from Sn targets under this pressure of He. The results are summarized in the data shown in Fig. 10(d), in which the angular distribution of the atomic flux in this case is shown. As can be seen, there is now no noticeable angular dependence of the captured particles. In addition, under the conditions of static background gas flow used in these experiments, the deposition thickness is reduced by a factor of ~5. The use of a background gas as a debris mitigating technique is discussed further in Section 5. Under these background gas conditions, we would expect no change in the character of the 13-nm soft-x-ray emission from the plasma. Figure 11 shows the approach that is used to measure the emission at 13 nm from a laser plasma. Two multilayer coated mirrors reflect radiation from the target at 45°. The multilayer mirrors are Mo–Si coated with a 9.06-nm layer separation, providing a high-contrast bandpass filter for 13-nm radiation. The radiation is detected with a fast, calibrated planar Al cathode photodiode, in front of which is a thin metal film filter to block visible and extreme ultraviolet from adding to the diode signal. It is estimated that the bandpass has a width of ~3% at the optimum mirror wavelength.

5. Implications for High-Repetition-Rate X-Ray Sources for Projection Lithography

This study in no way attempts to present a comprehensive treatment of the optimum requirements of a laser plasma soft-x-ray source for projection lithography. Its scope is limited. It presents some data on the particle and plasma emission from laser plasmas currently considered to be operating in the regime that provides high enough x-ray conversion efficiency to be feasible for soft-x-ray lithography. In this study we have made an initial examination of the various types of particulate emission from the plasma, drawing a distinction between ionized particles, neutral atomic flux, and so-called clusters or hot rocks or large globular clumps of target material ejected from the target zone. Partly as a consequence of the sensitivities of the diagnostics that we use in this study, we analyze separately the large clusters, down to ~10 μm in size, and the atomic flux, which is assumed to be much smaller in particle size, even monatomic. So far we have no diagnostic that isolates particles that are smaller than 10 μm but larger than single atoms separately from the total atomic flux. This covers more than 3 orders of magnitude in particle impulse energy. However, to the best of our knowledge this study does quantify two particular parameters fairly accurately for the first time: an assessment of the mass ablated as atomic flux and a measure of the cluster emission from the plasma. From this study several conclusions that have profound implications for the use of laser plasmas in soft-x-ray projection lithography can be drawn.

The observation of cluster emission from laser plasmas produced from target materials that are efficient converters of laser radiation to 13-mm x rays has significant implications for the use of a high-repetition-rate x-ray source in an operational lithography system. As noted above, the specific impulse of these particles is high enough to puncture available thin-film x-ray filters and to damage irrevocably the x-ray and the optical components that would be in

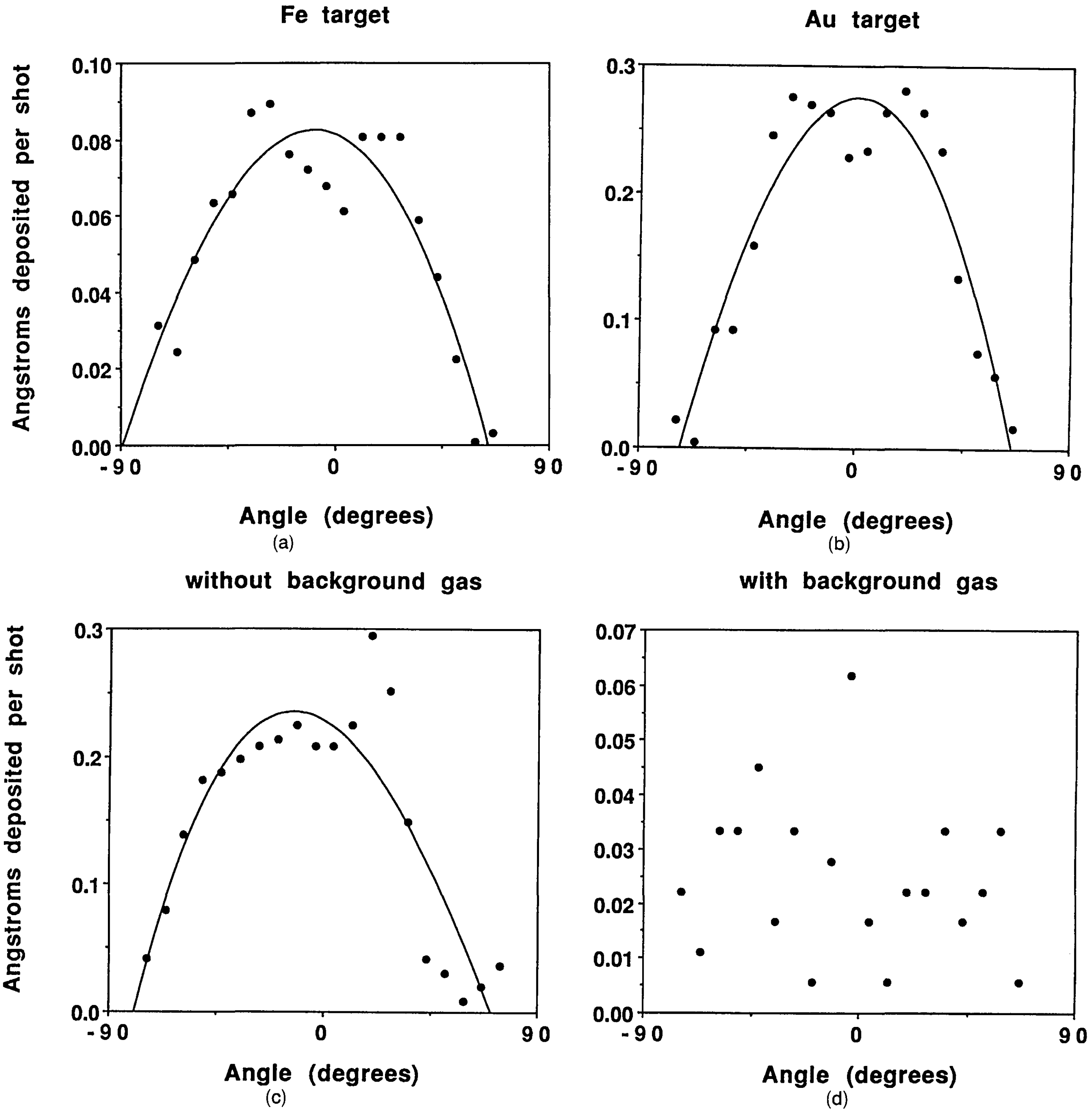
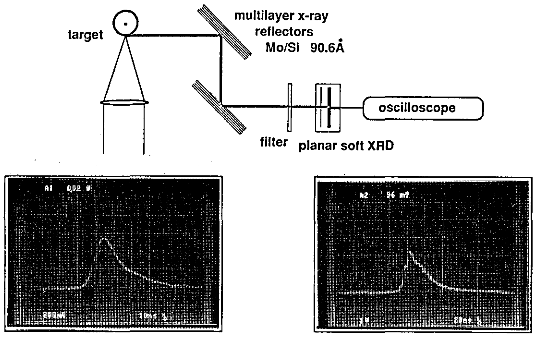


Fig. 10. Angular distribution of atomic flux deposition per shot for (a) Fe (b) Au (c) Sn, (d) Sn under a background of 0.2 Torr of He.

their path in an operating lithography system. In principle, it may be possible to impede their path between the plasma and these delicate and costly optical components. Several possible techniques have been suggested. These include (1) the use of spinning apertures, (2) the use of pulsed gas or particle jets to deflect these particles to benign collectors, (3) the use of magnetic deflection after these particles have been charged with a high-current electron beam, and (4) the use of laser light ablation of the particles to deflect them away from sensitive optics. However, none of these approaches is technologically elegant. For example, the use of a spinning aperture would imply some undesirable technical requirements. Consider the use of a rotating aperture designed to inhibit the particles measured in this study. These particles have velocities in the range 200–2500 cm/s. A simple configuration would be one as shown in Fig. 12. Assuming that the aperture has a diameter of 1 cm and is spaced 1 cm from the target, to inhibit these particles emanating from a 200-Hz x-ray source would require the spinning disk to have a diameter of > 10 cm and to rotate with a speed of > 10,000 rpm. Although this capability is within current technology, the desirability of situating such a continuously operating system in close proximity to expensive, critical optical components without maintenance for periods of months may be questioned.



laser pulse (10ns/div) 130 Å emission (20ns/div)

Fig. 11. Top: Experimental setup used to measure 13-nm radiation from laser plasma. Bottom: Examples of the laser pulse shape (left) and the x-ray emission pulse (right) are shown.

An alternative to the above approach is to take advantage of the observation made in this study that for virgin target irradiation, no cluster formation was observed. Before discussing possible consequences of this observation, several caveats should be made. First, although in this study we consistently observed no cluster formation for virgin target irradiation from a variety of targets, this may be dependent on the irradiation conditions. It has been noted, for instance, that in the use of longer pulses at shorter wavelengths (248 nm), there is some evidence of cluster formation.[19] Moreover, since the technique we are currently using has a spatial resolution limit of ~ 10 μm, it is possible that particles of smaller size are not being detected in our experiments.

The economic costs of avoiding the generation of clusters in the x-ray source may not be very attractive. Consider the following implications for a 400-Hz laser plasma x-ray source operating with some type of solid target system, such as a rotating drum or a tape drive, which presents a new target surface to the laser beam for each shot. If these target points are separated by ~ 1 mm the target surface must move at a speed of 40 m/s. The minimum new target surface area required for each operating period of a lithographic facility, which is assumed to be 8 h, will be ~ 120 m^2. The logistics of the material feedthrough would not be insignificant. Moreover the cost may be prohibitive. Accepting the estimated cost per shot requirement from the system analysis for an operation laser plasma x-ray source-based lithographic installation made by Ceglio and Hawryluk,[18] that is, a cost of $10^{-6} per shot, would place an upper limit of approximately $1 for the cost of each 8-h target element. This implies a maximum target area cost of <1 ¢/cm^2. If a tape target were used, for instance, the cost for the target tape must be <$1/km. These requirements may be difficult to achieve. They may imply that the use of a solid, planar moving target providing a virgin target surface per shot is not a feasible option for a soft-x-ray lithography laser plasma source.

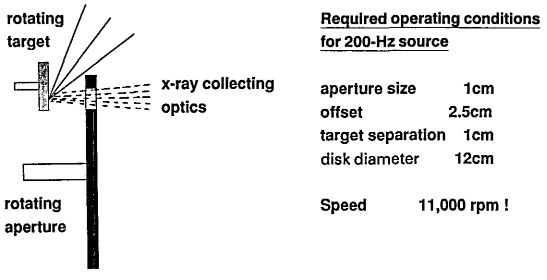


Fig. 12. Rotating-aperture cluster-inhibiting system for a high-repetition-rate soft-x-ray laser plasma source.

The consequences of considering the mass of target material ablated as atomic flux are also disturbing. From the measurements reported here, a logical extrapolation to a 400-Hz source would imply exceedingly high mass flows and unacceptable mass deposition on x-ray and optical surfaces over a reasonable operating period. Ceglio and Hawryluk,[18] for example, assume that the principal optical elements in the vicinity of the source would be exchanged every three months, that is, after some 3×10^9 shots. For example, from measurements shown in Fig. 10, the target mass deposition on a surface, such as an x-ray collector mirror, situated 50 cm from the target in vacuum, would be ~300 mg/cm^2, or 400 μm thick. One approach to reducing this deposition rate without significantly reducing the x-ray emission would be to use targets with a thickness equal to the laser ablation depth (~300 nm under the present conditions). Here we do not address how such a target could meet the cost requirements stated above. The reduction in the mass deposition rate would be a factor of ~20. Moreover, from the measurements reported here, the use of a He background gas reduces the atomic flux sticking rate by a factor of ~ 10. The adoption of these two approaches would reduce the deposition rate to ~ 2 μm per 3-month interval, still a factor of ~ 10^3 more than is tolerable. A flowing He system might be more efficient in extracting this metallic aerosol. Such a system will require some type of filtering system for isolating the ablated material.

6. Summary

The measurements reported here and the conclusions drawn from them raise important questions regarding the feasibility of using laser plasma sources, as they are configured at present, on the solid target for soft-x-ray projection lithography. They imply that fresh directions should be pursued toward satisfying the requirements of a high-repetition-rate laser plasma source. Central to these is the reduction of particulate matter emission from the source. This implies the employment of an interaction regime in which the energy imparted to kinetic motion of particulate matter, particularly large clusters of neutral atoms, must be avoided. In addition to this requirement is the observation that manipulation of the plasma conditions to maximize the conversion of laser light into radiation useful to projection lithography will have an impact on the overall requirements in two ways. First, it will reduce the level of nonuseful x-ray radiation and lessen radiation damage on the first x-ray condenser mirror. Second, an increase in the useful x-ray conversion efficiency will reduce the overall laser output requirements. Finally, the high-repetition-rate and long continuous lifetime requirements of the source will place strict levels of cost and performance on target and laser systems.

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