Laser-produced plasmas for soft x-ray projection lithography

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Laser-produced plasmas are one of the most likely sources to be used for soft x-ray projection lithography. The characteristics of these sources are described in terms of the expected radiation efficiency within the illumination bandwidth of a lithographic system. Measurements of the plasma particulate emission are described and techniques for interdicting this emission before it reaches the illumination optics are discussed. The laser requirements are obtained for a lithographic system producing a wafer rate of 60, 6 in. wafers per hour.

I. FUTURE LITHOGRAPHY REQUIREMENTS

The demand for greater information processing capabilities, at lower cost, places a continuing pressure on microchip manufacturers to produce more sophisticated microprocessing chips. These chips must not only have the capabilities of higher processing rates but also have more features on each chip. Manufacturers accomplish this by shrinking the size of each element on the chip and also by increasing the chip size. The biggest driving force in reduction of feature size is the production of memory chips. By the turn of the century, minimum feature sizes of less than 0.2 μm will be required in order to manufacture a 1 Gbit dynamic random access memory (DRAM). Such small feature sizes will most likely be beyond the capabilities of optical lithography even with the use of phase-shift masks. The only likely alternatives at this point, for high wafer throughput manufacturing facilities, would be x-ray proximity lithography, projection e-beam lithography, or soft x-ray projection lithography (SXPL). This article will briefly summarize the advantages of SXPL and specifically address the issues relating to the use of a laser-plasma source for this type of lithography.

II. ADVANTAGES OF SOFT X-RAY PROJECTION LITHOGRAPHY

There are two primary advantages in using an imaging or projection type of lithography. First, it is a parallel type of process that causes patterns to be produced over an entire chip area simultaneously, thereby significantly reducing the time required to expose the entire wafer. Second, the imaging process allows the mask pattern to be much larger than the pattern on the wafer due to the reduction capability of the imaging optics. This can significantly reduce the cost of the mask since larger mask features are much easier and less costly to fabricate than smaller features. This lower cost estimate is based upon the assumption that the decreased cost of the larger features would far outweigh the cost of a larger mask, which is probably reasonable since the total number of information pixels would be the same in each case. SXPL takes advantage of these imaging capabilities by offering the possibility of producing very small feature sizes (0.1 μm) while maintaining a large depth-of-focus (DOF) (± 1.0 μm). The large DOF is very desirable to be able to provide adequate leeway in the manufacturing process.

By considering the fundamental effects of diffraction, the above requirements for minimum feature size and DOF can be shown to place strict limitations on the illumination wavelength and the numerical aperture (NA) of the imaging optics. A simple analysis,[1] using the Rayleigh criterion, indicates that the illumination wavelength must be 200 Å or less and the NA of the imaging optic must be less than or equal to 0.1. Fortunately these wavelength and NA requirements can be achieved by taking advantage of two relatively recent technological advances. The first is the development of highly reflective multilayer optical coatings in the soft x-ray spectral region[2] in the wavelength region from $\sim$50 to 300 Å. Multilayer reflection coatings of up to 63% have recently been achieved[3] at a wavelength of 130 Å using coatings consisting of alternate layers of molybdenum and silicon. Thus the most desirable wavelength for SXPL is presently at or near 130 Å since a lithography system would most likely involve seven or more reflecting surfaces and the optical throughput is, therefore, very sensitive to mirror reflectivity.

The second technological advance is the development of large field diffraction limited reflective imaging optics[4] with NAs that satisfy the above requirements. Recently designed optics that will provide such imaging are advanced designs of the ring field type.[5] They produce an arc-shaped diffraction-limited image of $\sim$2.5 cm length and 0.1 cm width ($\sim$0.25 cm^2) on the wafer at a 5:1 reduction from mask-to-wafer. Such optics are axially symmetric, distortion corrected, telecentric at the wafer, and near telecentric at the mask.

III. POSSIBLE SOURCES FOR SOFT X-RAY PROJECTION LITHOGRAPHY

Possible sources that have been considered for SXPL include synchrotrons, laser-produced plasmas (referred to here as laser plasmas) and discharge plasma sources. Of these, only synchrotrons and laser plasmas have currently been demonstrated to have the capabilities necessary for SXPL.

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Synchrotrons are reasonably efficient, their energy can be concentrated in a relatively narrow wavelength spectrum, they produce a continuous beam, and they are relatively reliable. Their disadvantages include very high cost, high spatial coherence, and potentially large down time if a fault occurs. From the standpoint of high cost, most likely a number of lithographic machines would have to be attached to a single synchrotron source, thereby creating a particularly undesirable disruption when a breakdown occurs. Some of the first SXPL experiments were carried out at the NSLS synchrotron using 130 Å light in which features of less than 0.1 μm were obtained in photoresist.[6]

Laser plasmas have advantages of relatively low cost, compactness, and potentially high reliability. The disadvantages include low efficiency, the necessity to control the debris from the plasma, and the fact that the technology has not yet been completely developed for this source. Successful demonstration of SXPL using a laser-produced plasma source has recently been made yielding 0.1 μm features.[7]

IV. EMISSION CHARACTERISTICS OF LASER-PLASMA SOURCES

A laser plasma soft x-ray source consists of a dense high-temperature plasma of highly ionized ions and associated electrons emitting a radiation spectrum that is characteristic of matter at such a high temperature. The plasma is produced by focusing a short-pulse laser (typically 10^{-8} s duration) onto a solid target at an intensity of the order of 10^{11}–10^{12} W/cm^2. The focused laser energy is absorbed by the target material, thereby heating the material and eventually stripping the electrons from the material. As the plasma is heated, more and more electrons are removed from each atom of the plasma and the atomic ions move to higher ionization stages. As they move to higher stages, they access higher energy levels and the radiative decay from these levels produces short wavelength radiation.

Due to the small absorption depth of the laser radiation incident upon the target material (typically 100–250 Å), only a very thin layer of material is initially heated and ionized. As it is heated, the material expands and the density is reduced, producing a density gradient of plasma atoms and ions decreasing with distance from the solid surface. The density of solid material is of the order of 5×10^{22} atoms/cm^3. The plasma density at which absorption of the laser energy occurs most efficiently (by inverse Brehmstrahlung) occurs at 10^{21}/cm^3 for a wavelength of 1.06 μm and varies with the inverse square of the wavelength. For shorter wavelength lasers, the energy absorption and plasma heating would occur at a location much nearer the solid material than that for the 1.06 μm laser. For example, if a laser operating at a wavelength of 248 nm (KrF excimer laser) is used to produce the plasma, the absorption would occur at a plasma density of over 1.6×10^{22}/cm^3.

The brightness and wavelength of the plasma emission are dependent upon both the specific target material and the laser intensity. A typical example is shown in Fig. 1 for a solid tin (Sn) target.[8] It can be seen that the emission occurs over a broad spectrum with a number of sharp features superimposed upon the broad background.

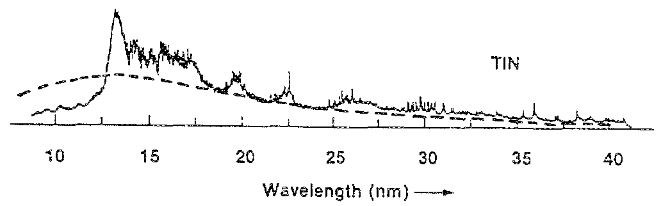

FIG. 1. Tin (Sn) plasma emission spectrum overlaid with the shape of a blackbody spectral distribution of temperature $T=225\,000$ K (20 eV).

The broad emission of such a plasma is found to be sensitive to the laser intensity and can be characterized by a temperature associated with that of a blackbody radiator. Such a blackbody spectral distribution, of temperature 225 000 K (20 eV), is shown superimposed (as a dashed curve) upon the Sn spectrum of Fig. 1 and was chosen to have a maximum emission at 130 Å, the optimum wavelength for the Mo:Si multilayer reflectors and the wavelength currently contemplated for SXPL. The sharp emission peak at 130 Å, enhanced above the blackbody spectrum, makes Sn an attractive target material for a laser plasma source for SXPL.

Assuming that the plasma radiates as a blackbody, the maximum energy E emitted from such a plasma of temperature T(K), emitting blackbody radiation of wavelength λ(cm), from a surface area πr^2(cm^2), over a spectral bandwidth $\Delta\lambda$(Å), for a duration Δt(s), can be expressed as

$$E(\lambda,T)=\frac{3.75\times10^{-2}}{\lambda^5[\exp(1.44/\lambda T)-1]}\,\Delta\lambda\pi r^2\Delta t \quad \text{(joules)}. \tag{1}$$

For a 200 μm diam plasma emitting at 130 Å over a bandwidth of 3 Å (the maximum bandwidth that would pass through a SXPL imaging system) and emitting for a duration of 10^{-8} s (the duration of a typical laser plasma), the emitted energy would be 2.3×10^{-4} J for a single pulse from a 20 eV laser plasma. For the case of a Sn plasma, additional emission above that of the blackbody emission could arise from the sharp spectral features associated with Sn as indicated in Fig. 1.

The radiation efficiency η of a blackbody radiator at a specific wavelength λ and temperature T can be obtained by dividing the energy E emitted at that wavelength and temperature by the total energy emitted by the blackbody radiator at all wavelengths (at that temperature) as obtained from the Boltzmann law ($I=\sigma T^4$ where $\sigma=0.567\times10^{-11}$ W/cm^2 and T is in K). For a wavelength of 130 Å and a bandwidth of 3 Å, η is given by the expression

$$\eta=\frac{4.57\times10^{21}}{[\exp(1.1\times106/T)-1]T^4}, \tag{2}$$

where T is in K. A plot of η versus plasma temperature, shown in Fig. 2, goes through a maximum of $\eta=1.49\%$ at

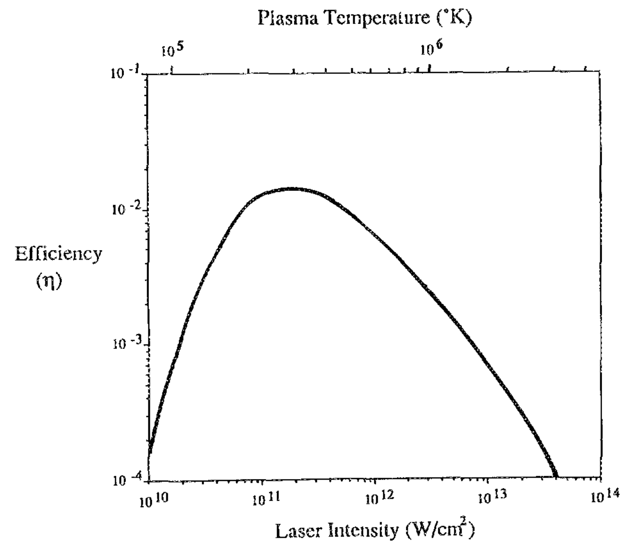

FIG. 2. Radiation efficiency vs plasma temperature and laser intensity for a blackbody radiator emitting within a 3 Å bandwidth at 130 Å.

$T = 280\,000$ K, which is a slightly higher temperature than that which produces a maximum emission at 130 Å.

An approximate relationship of the plasma temperature T to the incident laser intensity I_l can be obtained by equating the absorbed laser energy incident upon the target to the energy loss due to thermal conduction by the plasma electrons. This leads to an approximate relationship of $T = CI_l^{4/9}$ where C is a constant.[9] Although the exact value of the exponent and the value of C have varied with different experimental studies, the expression for T is a reasonably good approximation for the laser intensity region under consideration. From an experimental result in which the actual plasma temperature was deduced for a similar laser intensity and plasma size,[10] the value of C can be determined to be ~ 2.8 for a plasma temperature given in K and a laser intensity given in Watts/cm². Thus using this expression $T = 2.8 I_l^{4/9}$ in Eq. (2), the blackbody radiation efficiency η can be plotted in terms of laser intensity I_l instead of plasma temperature T and is also shown in Fig. 2. From this graph, it can be seen that the maximum radiation efficiency would be expected to occur at a laser intensity of just under 2×10^{11} W/cm².

Two separate measurements of conversion efficiency of laser plasmas have recently been made under conditions thought to be appropriate for laser plasma sources for SXPL. The conversion efficiencies obtained from these measurements are the total plasma radiation flux emitted from the target region in the given spectral bandwidth, divided by the incident laser energy on target and are therefore not the same as the radiative efficiency η. Measurements made at Lawrence Livermore National Laboratories were made with a frequency doubled YAG laser at 0.53 μm with a pulse duration of 7.5 ns.[11] Those made at Sandia National Laboratories were made with a KrF laser at 0.248 μm that had a 32 ns pulse duration.[12] A summary of these conversion efficiency measurements are shown in Table I. The 1% measured with the 0.53 μm laser at LLNL was made over a 3 Å bandwidth and thus is the most similar to the conditions used for the estimate of η from Eq. (2).

TABLE I. Experimental parameters and respective measured conversion efficiencies at LLNL and SNL.

Experimental conditions	Lawrence Livermore National Laboratory	Sandia National Laboratory
λ(laser)	0.53 μm	0.248 μm
I(laser)	2×10^{11} W/cm²	3×10^{11} W/cm²
Pulse energy	0.2 J	1.1 J
Bandwidth	3 Å	4.5 Å
Pulse duration	7.5 ns	32 ns
Plasma diameter	130 μm	150 μm
Target material	Tin(Sn)	Gold(Au)
Measured conversion efficiency	1%	0.8%

As stated previously, the conversion efficiencies of Table I are (energy radiated at 130 Å/laser incident energy) or $(E_{130\,Å}/E_{in}^l)$. Thus, $\eta = (E_{130\,Å}/\beta E_{in}^l)$ where β is the fraction of the incident laser energy converted to radiation. If we assume that $\sim 40\%$ of the energy incident on the target is converted to radiation ($\beta = 0.4$), which is not unreasonable,[13] then the LLNL value of η would be 2.5% which is about 70% above the maximum predicted value of 1.49% in Eq. (2). The additional 70% of the radiation above the predicted value is most likely due to the structured features that are superimposed upon the continuum in Fig. 1. This simple analysis suggests that the only way to increase the conversion efficiency would be to increase the structured emission features within the desired emission bandwidth, since increasing the blackbody temperature would only decrease the radiation efficiency η according to Eq. (2). These structured features are most likely associated with line radiation within more than one of the highly ionized stages[14] of Sn.

Based upon the preceding analysis and experimental results, a preliminary set of conditions can be summarized for producing optimum laser plasma emission for a SXPL system. These would include a laser with an intensity of $1–5 \times 10^{11}$ W/cm² with a pulse duration of the order of 10 ns irradiating a Sn target. Shorter time durations would decrease the total radiation flux. Longer durations would significantly increase the plasma debris. It is expected that refinements relating to laser pulse duration and shape, optimum laser wavelength, target material composition and thickness, and plasma diameter, will no doubt produce an enhancement above the preliminary values of conversion efficiency discussed in this article.

V. PARTICULATE EMISSION FROM LASER-PLASMA SOURCES

When a plasma is formed at the surface of a material by focusing a laser on that material, a portion of that material ablates from the surface and becomes a plasma of highly ionized ions and electrons as previously described. The energy of the focused laser that is absorbed by the plasma is channeled in two directions. First, it accelerates the electrons which in turn collide with and thereby accelerate the surrounding ions such that both the electrons and ions acquire very high velocities or effectively a very high temperature (225 000 K in this case). Second, the ions, via collisions with electrons, are stripped of many of their electrons to evolve towards very high ionization stages from which soft x-ray radiation occurs. Thus during the early stages of the plasma evolution, the highly stripped ions are the emitting species that provide the soft x-ray source, which in this case would be used as an illuminating source for SXPL. At the later stages of the plasma development, after the laser heating pulse has ceased, these ions are streaming outward from the target region with the velocities they have acquired from the plasma formation. Many of these ions recombine with the surrounding plasma electrons thereby reducing the stage of ionization. At some point in time after the ions have left the target region, they have been reduced to neutral atoms or lower ion stages of that species but they are still moving with high velocities. Also during the early stages the plasma electrons conduct heat into the remaining solid target material thereby heating and vaporizing that material causing a "puff" of vapor to evolve from the target material. Sometimes large particulate or clusters of that material (sometimes referred to as hot rocks) are also ejected from the surface region.

The particulate emission can thereby be classified into three categories. The first is high velocity atomic ions from the plasma. The second is neutral atoms vaporized from the heated target. The third is clusters, ejected from the target material. All three of these types of particulates have the potential to reach the illuminating optics and thereby damage the optical surfaces. In addition, the presence of the atoms and ions can lead to absorption of the soft x-ray flux before it reaches the optics and mask. It is thus important to measure the amounts and velocities of these particulates and to develop techniques to intercept or deflect them to prevent them from reaching those optics.

VI. MEASUREMENTS OF PARTICULATE EMISSION

A. Cluster emission

In order to characterize the cluster or "hot rock" emission from a solid target a stroboscopic photographic technique was employed. This technique utilized a 511/578 nm copper vapor laser (CVL)[15] operating at a pulse repetition frequency of 14 kHz with pulse energy of 3 mJ and pulse duration of 50 ns. The 25 mm diam CVL beam was situated parallel and directly in front of a rotating solid target material (Sn,Au, or Fe). The plasma was created by focusing the output of a Nd:YAG laser at 1.06 μm and 500 mJ per pulse onto the target in a focal spot of 140 μm diam. This beam was incident at 45° to give near normal emission from the target surface and reduce incident laser light and plasma interaction. The ejected particles were illuminated by the CVL light approximately every 74 μs, thus creating a slow motion effect. This is seen as a sequence of bright dots created by light scattering from the particles. This effect was photographed at 1:1 magnification with a film camera situated above and normal to the plane containing the Nd:YAG and CVL beams. This configuration is shown in Fig. 3.

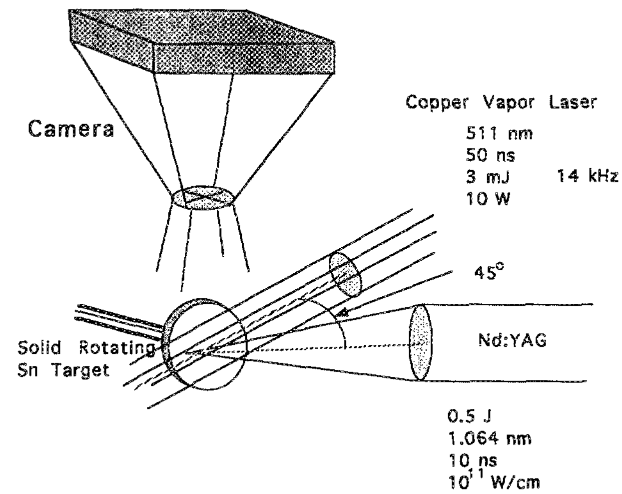

FIG. 3. Schematic diagram of setup used to photograph particles. Clusters are illuminated by the copper vapor laser and imaged at 1:1.

Using this technique, several types of information were obtained by analyzing the trajectories as recorded on film. By measuring the cluster size and separation it is possible to determine mass and velocity. In addition, angular distribution and total mass may be estimated. In experiments on clean target surfaces, minimal large cluster emission (greater than 50 μm) was observed. It was found that large cluster emission increased when progressive laser shots were made on the same spot, thus creating a crater in the target. In preliminary experiments performed using such a cratered surface on Sn targets, particle sizes were observed to range from less than 10 μm to over 200 μm. Velocities were found to range from 200 to 2500 cm/s using this technique.

B. Atomic and ionic particle flux

The combined atomic and ionic flux were measured using acetate collecting plates in front of the plasma as shown in Fig. 4. These plates would then indicate the angular distribution of the flux as well as the total amount of flux. Optical transmission through the acetate as well as profilometer measurements were then used to determine the amount of flux per pulse. This amount measured for a Sn planar target is shown in Fig. 5 as a function of angle from the target normal for conditions of vacuum and also for

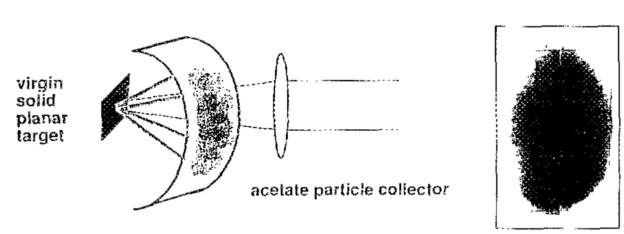

FIG. 4. Technique indicating acetate collection of atomic and ionic flux.

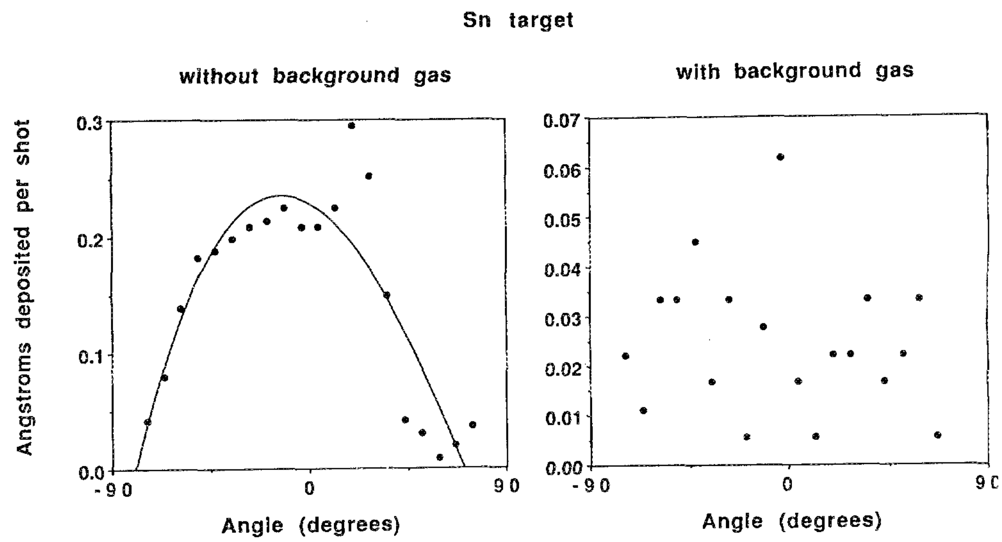

FIG. 5. Measurements of flux per pulse from a Sn target as a function of angle under vacuum and with 0.05 Torr of helium as a background gas.

conditions of 0.05 Torr of helium as a background gas. It can be seen that the helium significantly reduces the flux reaching the acetate as well as randomizing its distribution. These data were taken for a fresh or new target for each laser pulse. Targets of gold and iron produced less flux per shot than for tin targets but similar angular distributions.

Table II summarizes some of the measurements as well as the best estimates of those quantities that are still in the process of being measured. These quantities include both the number of particles per laser pulse of each type and the velocity of those particles. These quantities will be useful in Sec. VII in analyzing how to prevent the particulates from reaching the collecting optics for a lithography system.

VII. POSSIBLE TECHNIQUES FOR INTERDICTING THE PARTICULATE EMISSION

The possible methods of preventing the particulate emission from reaching the collecting optics include mechanical interruption, gaseous interruption, deflection with magnetic fields (charged particles), and possibly laser interdiction. Of these, the first two appear to be the most likely possibilities. The interdiction of each of the types of debris of Table II will be discussed separately since they may require different techniques.

TABLE II. Quantity and velocity estimates of the three types of particulate emission per laser pulse.

Particle type	Quantity/pulse	Velocity
Neutrals and slow ions	Up to 5×10^{14}–5×10^{15} (maximum)	Up to 5×10^{4} cm/s (estimated)
Ions	Up to 5×10^{14} (probably much less)	Up to 10^{7} cm/s (estimated)
Clusters	Several	200–2500 cm/s

A. Atoms and ions

The atomic and ionic particle flux/pulse combined with the required pulse repetition rate of 1 kHz (as shown in Sec. VIII) leads to a generation of from 5×10^{17} to 5×10^{18} atoms and ions/s to be removed or 5×10^{-5} to 5×10^{-4} g/s. This amounts to a substantial quantity of mass that must not only be blocked from reaching the collecting optic but also must be removed from the target region since it represents an accumulation of up to 1 g/h of debris. For example, it could be potentially deleterious to the operation of a mechanical interruption device by causing significant mass buildup on moving parts. The use of a flowing buffer gas, probably helium, is the most likely solution to the problem of atomic mass removal. It has been shown previously that the use of a small amount of buffer gas (0.1 Torr helium) reduces the amount of debris reaching a collecting plate 1.5 cm from an iron target by a factor of 10 when using a 248 nm KrF excimer laser to produce the plasma.[15] Results in our laboratory are similar in that we have shown a reduction of a factor of 7 for a tin target at a distance of 3.0 cm with a helium pressure of 0.05 Torr and using a 1.06 μm YAG laser to form the plasma. Significant debris reduction at this pressure is fortunate since a gas pressure any higher would absorb the 130 Å radiation before it reaches the illuminating optics. For example the absorption cross section for helium at 130 Å is 0.016/cm Torr and for hydrogen is 0.002/cm Torr.[17] Other gases have higher absorption coefficients than this and would therefore probably be less useful.

The relevant factor in the removal of the atomic flux by a buffer gas is that the gas impart enough momentum to the atomic and ionic flux, in the transverse direction from the target normal, to change the direction of the flux moving toward the collecting optic. In order to do this, the momentum of the buffer gas moving transversely must be at least as great as the momentum of the atomic flux. The momentum would then be effectively transferred since the mean free path between collisions of the buffer gas with the atomic neutral flux is of the order of 0.1 cm at these pressures. Since the density of the buffer gas is of the order of $5\times10^{15}/\text{cm}^3$ and the gas could be flowing at velocities of up to 10^5 cm/s (for helium), the momentum would be of the order of 4×10^{-3} g cm/s per cm^3 of helium. This could be compared to the momentum of the atomic flux of up to 5×10^{-2} g cm/s using the maximum velocity data summarized in Table II for neutral atoms. Since this momentum is somewhat higher than the transverse helium momentum, the neutral flux must be reduced by an order of magnitude, as also suggested in Table II, or a greater path length over which the helium could interact must be used. Thus a transversally flowing gas, exiting from a nozzle or multiple nozzles would probably be the best solution for the removal of this type of particulate emission.

B. High-velocity ions

The removal of the high-velocity ions would be more difficult since the momentum/particle is much higher. Fortunately, the quantity of these particles is expected to be significantly less than for the atomic flux moving at lower velocities. Small quantities of these ions therefore could also be taken care of by a rapidly flowing buffer gas since the total momentum of the ions would be much less than the transverse momentum of the buffer gas. Measurements are being made of this flux and its velocity to be able to more accurately determine the parameters necessary for interdiction.

C. Clusters

Clusters (small chunks of material of various sizes) pose a serious problem. These clusters can range in size from hundreds of angstroms to hundreds of microns. As pointed out in Sec. VII B, it is fortunate that for flat (fresh) target surfaces the cluster emission is much smaller than for targets that have been subjected to multiple shots and thus become pitted. It is therefore anticipated that a target arrangement (most likely a continuous strip of thin target material, possibly coated on a thin inert backing material) that provides a fresh target for every pulse will be used for a SXPL source. The cluster emission from such a target will therefore be minimized and consequently the problems associated with such clusters in damaging the illuminating optic will be either eliminated or reduced to tolerable levels if interdictive devices are used. The interdiction of clusters will most likely require mechanical means. The use of a thin film tape filter of thickness small enough to transmit the soft x-ray flux at 130 Å (of the order of 0.5 μm) would be costly and may not be able to stop the debris from passing on through the film and reaching the optic. In addition, the cost of such a device would most likely be prohibitive. An analysis by LLNL suggests that the cost of each target shot, in this case including the tape filter, could be no more than 10^{-5} dollars/shot.[18] It does not seem likely that the filter could meet this requirement since it would have to have a relatively large surface area in order to be sufficiently far enough away from the plasma source to prevent it from being damaged by the atomic and radiation flux before the clusters reach the filter.

Thus a mechanical device, such as a rotating disk, will probably be required to interdict the clusters. However, using such a disk is not a simple solution to the problem. Assume that a rotating disk with a 1 cm diam hole is located one cm from the target and rotating on an axis normal to the target. In order for that device to interdict clusters with velocities up to 2500 cm/s the disk would have to rotate at a speed of 10 000 rpm if the distance from the center of the disk to the center of the hole is 2.5 cm. Such a speed is not impossible to achieve but would require a motor that is capable of operating in a low pressure environment and not emitting any vapors or other particulates that would lead to absorption of the soft x-ray flux. It will be shown in Sec. VIII that the laser repetition rate might have to be as high as 1000 pulses per second which would therefore require a rotational rate of up to 60 000 rpm for a single hole in the disk. Increasing the size of the disk would reduce the required rate of revolution, but the moment of inertia of the disk would increase as the square of the disk radius thereby placing significantly larger demands upon the stability of the disk while rotating. Placing more holes in the disk to reduce the rotational speed requirements may not be an alternative due to the need to intercept the slowest as well as the fastest particles. In order to intercept the 200 cm/s particles as well as the faster particles, only one hole could be located in a disk rotating at 10 000 rpm for example.

The possibility of significant mass accumulation, in an uneven distribution, could unbalance the disk to a point where it would not operate at a high speed. Many of the clusters would bounce off of the disk, but some would stick and also a significant number of atomic size particles would also accumulate. A gas flow system would be essential to reduce the mass flux arriving at the disk but may not inhibit the accumulation of clusters. Experiments are necessary to determine the mass accumulation and thus determine the lifetime of a disk before replacement is necessary.

VIII. FLUX REQUIREMENTS AND LASER REPETITION RATE

Estimates of the flux requirements of a laser plasma source for SXPL can be made assuming a production throughput of 60 6 in. wafers per hour or an exposure rate of 3 cm^2/s. If we also assume a resist sensitivity[19] at 130 Å of 10 mJ/cm^2, then the power required at the wafer would be

$$3\ \text{cm}^2/\text{s}\times10\ \text{mJ/cm}^2=0.03\ \text{J/s}=30\ \text{mW}.$$

For a laser energy of 1 J/pulse and a 1% conversion efficiency into the 3 Å bandwidth around 130 Å, 10 mJ/pulse of useful soft x-ray radiation would be available. Assume 10% of the useful soft x-ray radiation emitted from the source is collected by the first illumination optic. Also assume that a seven mirror optical system is used (from source to wafer), with mirror reflectivity of 60% per mirror, such that the fraction of the light transmitted through the optical system is $(0.6)^7=2.3\%$. This implies that 2.8×10^{-5} J/pulse will reach the wafer. In order to meet the requirements of 30 mW outlined above, a repetition rate of 1000 Hz (1 kHz) would be required for the laser system.

A number of factors could be improved upon to either lower the pulse repetition rate or lower the energy/pulse requirements. The resist sensitivity could be reduced to a range of 1–5 mJ/cm^2. This possibility has been suggested in the literature[20] and is not an unreasonable value when it is considered that most materials absorb very highly at 130 Å and thus a small amount of energy can yield a very high absorbed energy density in the top surface of the resist.

Mirror reflectivities might be improved above 60% per surface. Such values have in fact been achieved in the laboratory. The highest reflectivity for a Mo:Si mirror is 63% and maximum theoretical reflectivity[21] is ~70%. Thus increasing the reflectivity from 60% to 70% for seven surfaces would reduce the flux loss by nearly a factor of 3 which is a very large energy savings.

Increasing the x-ray conversion efficiency above 1% is also a very likely possibility. An increase of a factor of 2 might be possible based upon the arguments given earlier in this paper, if more energy can be channeled into line emission rather than blackbody emission.

Also increasing the collection efficiency of light emanating from the source might be possible. One problem associated with this is the larger the NA of the collecting optic, the more difficult it might be to remove the plasma debris. It is much easier to periodically interrupt a small aperture at a rate of 1 kHz than a large aperture. The first collecting optic would most likely be located at a distance of between 5 and 50 cm from the laser-plasma source. For a small collecting NA the distance is not as important an issue as it would be for a large NA optic due to the large cost increase for larger diameter optics. On the other hand, the closer the optic is to the source, the more the optic would be subjected to the debris, since it would have less buffer gas between it and the plasma source. These issues are closely related to the design of the collecting optic and the flux requirements of the source and therefore could vary significantly from one illumination system design to another.

IX. POSSIBLE LASER SOURCES

A laser requirement of 1 J/pulse with a 10 ns pulse duration operating at a repetition rate of 1 kHz is a fairly demanding requirement and is beyond the present state-of-the-art. The closest that present day commercial lasers come to meeting this requirement is a 0.67 J/pulse excimer laser[22] operating at 308 nm at 300 Hz or a 1 J/pulse Nd:YAG laser[23] operating at 1.06 μm at 30 Hz. These lasers are limited in repetition rate primarily by the cooling requirements, in the case of the solid state laser, and by the power input requirements in the case of the excimer laser.

Diode-pumped solid-state lasers have been operated at 1.06 μm in the laboratory at a 1 J/pulse level at a 50 Hz repetition rate[24] and also at a 0.1 J/pulse level at a 1 kHz repetition rate.[25] Diode-pumped solid-state lasers will most likely be the lasers eventually used for factory lithographic systems. They are compact, very efficient, and offer high reliability. Due to their pumping wavelength they also offer a minimum heat transfer to the laser material during the pumping process. At the present time the cost is quite high for such lasers but has come down significantly in recent years and by the time SXPL becomes a practical process, the cost of laser diodes should be very reasonable thereby keeping the laser cost to a small fraction of the total lithographic system.

X. FUTURE DIRECTIONS

Several areas of investigation are necessary in order to perfect a laser plasma source for SXPL. These include laser source development, characterization of plasma particulates, design and testing of particulate control techniques, and development of advanced target designs to improve x-ray conversion efficiency.

As far as laser source development is concerned, the emphasis should be on high-repetition rate solid-state laser development. Devising techniques for optimally pumping a laser rod or slab efficiently at high-repetition rate with laser diodes should take first priority. Excimer lasers will play a role in SXPL in the short term but in the long term they will never be as efficient, or compact, or reliable as a solid-state laser system.

Continued characterization of plasma particulates will move in the direction of making measurements on thin targets including mass limited targets. Also the velocity of the atomic particle flux will be measured using optical absorption techniques. Efforts will be made to identify submicron size clusters and measure their velocities.

Debris control techniques will include interdiction devices such as rapidly rotating disks. Mass removal with flowing gases should also be investigated. Other possible debris deflectors could include magnetic fields and laser interdiction (a laser irradiating the plasma at a direction normal to that of the collecting optic).

Target design should include shaped targets, mass limited targets, multimaterial targets, and layered targets. Also laser pulse shape and duration should be investigated in terms of their effect on conversion efficiency.

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