Status of the liquid-xenon-jet laser-plasma source for EUV lithography

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ABSTRACT

The liquid-xenon-jet laser-plasma source is one of the extreme-ultraviolet (EUV) source technologies under development for EUV lithography. This paper presents some recent improvements of the technology, including the ability to operate a stable plasma at a distance of 50 mm from the nozzle, the first positive mirror-lifetime results, and improved laser-to-EUV conversion efficiency of 0.75 %/(2%BW 2πsr) at λ=13.45 nm.

Keywords: EUV lithography, laser-produced plasma, liquid jet, xenon

1. INTRODUCTION

Extreme-ultraviolet (EUV) lithography[1] at $\lambda \sim 13.5$ nm is currently the strongest candidate to succeed deep-ultraviolet lithography for large-scale manufacturing.[2] The EUV radiation source has, however, been identified as one of the largest obstacles towards realization of EUV lithography since no source technology currently meets all the required specifications for a production tool. Nonetheless, several source concepts, all based on hot plasmas, are under intense development.[3] These include electrically driven plasmas such as, z-pinch, plasma focus, capillary discharge and hollow cathode discharge, as well as several laser-produced-plasma concepts.

The liquid-xenon-jet laser-plasma EUV source[4,5] is an especially attractive source technology since it combines the advantages of the microscopic-liquid-jet target method[6,7] and an inert-gas, high-Z target material.[8] An overview of the liquid-xenon-jet laser-plasma technology can be found in a previous paper,[9] while this paper will focus on recent results, including the ability to operate a stable plasma at 50 mm from the nozzle, some first encouraging mirror-lifetime experiments, and an improved laser-to-EUV conversion efficiency (CE).

2. BASIC REQUIREMENTS OF A EUVL SOURCE AND NEW IMPROVED CE

There is, still, no definite specification for the minimum required EUV source power for production scale EUVL steppers. The latest estimate of the required EUV power, that was jointly presented by the three main stepper manufacturers (ASML, Canon and Nikon), is 47–120 W.[10] This EUV power is defined at the focus of the collector optic and should be "spectrally pure", i.e., without significant out-of-band radiation, especially in the DUV and IR range. The factors influencing the amount of EUV power generated are of course both the laser-drive power and the CE to in-band EUV, as well as the solid angle of collection, the collector reflectivity, losses due to potentially necessary spectral filtering, losses due to potentially necessary debris mitigation schemes, and any losses due to absorption in the residual gases. Naturally, it is important to limit the necessary drive-power, both because it is difficult and expensive to generate high drive-powers and also, as will be discussed further below, since a high drive-power will lead to thermal issues. The necessary drive-power can be limited by the ability to use very high collection solid angle, as previously discussed for the liquid-xenon-jet laser-plasma technology,[9] and by reaching a high CE value.

So far, an average CE of 0.75 %/(2%BW 2πsr) at λ=13.45 nm has been reached with the liquid-xenon-jet technology, continuing the upward trend from previously published 0.1 %[11] and 0.55 %.[9] The CE was measured

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using the Flying Circus II tool,[12] as fully described in a previous publication.[11] Some absorption is also present in the approximately 1 m long measurement path due to the Xe background pressure of $\sim 3 * 10^{-3}$ mbar. The CE value has not been corrected for this absorption since, as mentioned above, the situation will probably be similar in a production-scale source. The achieved CE has increased continuously by optimization and we believe that it can be increased even further with continued optimization. A good indication of this is that a CE value of 1.2 %/(2%BW 2πsr) has been published for a solid Xe bulk target.[13] However, even with a 1.2 % CE value, ~11 kW of laser power is needed to reach the lowest required EUV power of 47 W, assuming a 2π steradian collector with 70 % reflectivity, a spectral purity filter with 50 % transmission, and that any potentially necessary debris mitigation schemes dos not absorb any EUV. The next section will discuss how such high drive-powers can be handled.

3. LONG WORKING DISTANCE

As noted in the previous section, the drive-power still needs to be in the 10 kW range even if high CE and high collection efficiency is obtained. Other techniques, such as discharge plasmas, that show lower CE and that cannot use high collection solid angle will require even higher drive powers. This power will give rise to severe heating of mechanical details in the vicinity of the plasma due to re-emitted and scattered out-of-band radiation as well as energetic ions and atoms. It has also been shown that the plasma will erode mechanical parts such as a nozzle in the vicinity of the plasma,[14] and that the material eroded will damage the sensitive condenser optics, thereby limiting the mirror life time. This problem will be even worse in discharge plasmas.

One of the main advantages of the liquid-xenon-jet concept is that target material is transported in a collimated beam, allowing for plasma production far from the nozzle and any other component. It is illustrated in Fig. 1 how a liquid-jet plasma operated far from the capillary nozzle will induce less nozzle heating and nozzle erosion than a gas-jet plasma operated close to the nozzle or a discharge plasma operated in the vicinity of both anode and cathode. Recently, as shown in Fig. 2, the distance to the plasma during stable operation has been increased to 50 mm. This

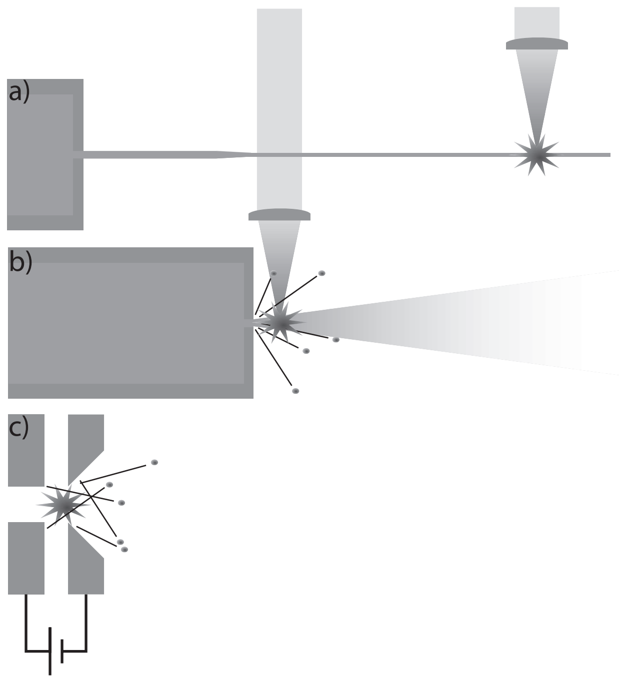

Figure 1. Schematic view of differences in harmful debris production and erosion between a liquid-xenon-jet laser-plasma source (a), a gas-jet laser-plasma source (b), and a typical discharge source (c).

is a very important and encouraging result since calculations show that the capillary nozzle will be exposed to less than 100 mW of power during 10 kW operation at this distance. Such an exposure will only increase the temperature of the flowing xenon by less than 5K. The achieved pulse-to-pulse stabilities at 50 mm and 20 mm from the nozzle

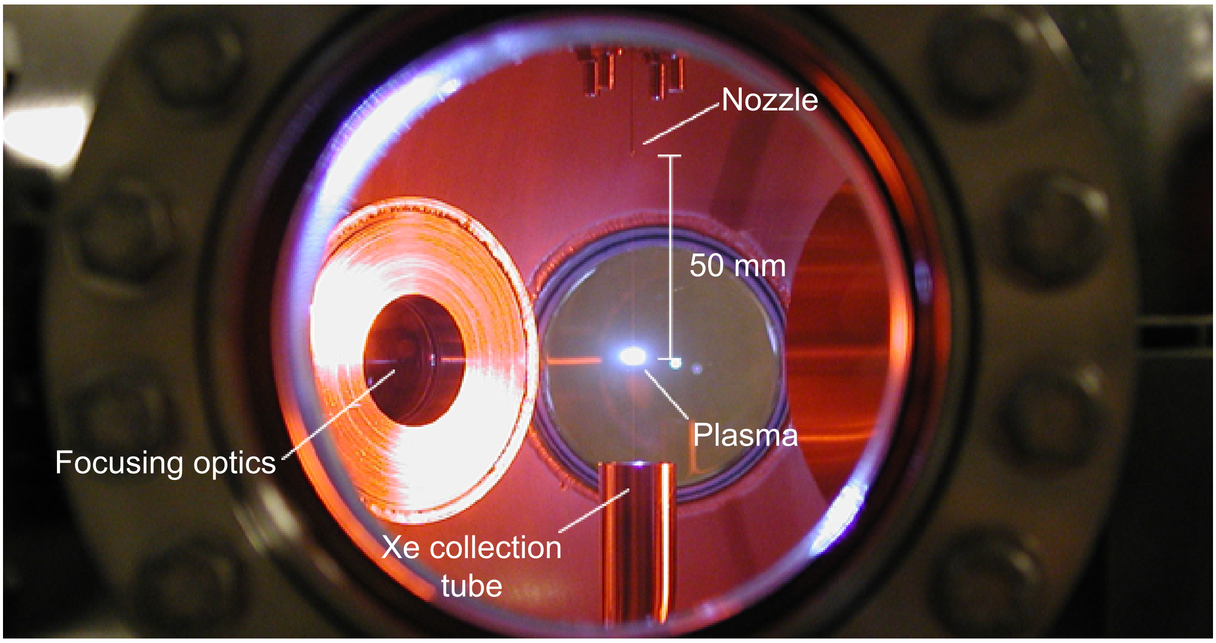

Figure 2. Picture of the liquid-xenon-jet laser-plasma source during operation. As can be seen the nozzle to plasma distance is 50 mm. The Xe collection tube can easily be moved further away due to the collimated nature of the liquid-xenon-jet and a new optical unit with 300 mm working distance is under development, minimizing possible sputtering, maximizing laser drive-power capabilities and giving unprecedented geometric access..

are shown in Fig. 3. The currently measured coefficient of variation at 50 mm from the nozzle, 5.6% - 1σ (16.8% - 3σ) does not yet reach the 3% - 3σ specified as the requirement for a production scale EUV source.[10] However, we believe that this value can be significantly improved by addressing issues such as the pulse-energy and beam-pointing stability of the laser and mechanical vibrations. Also, the next section will discuss how high-repetition rate operation can increase the dose stability during lithographic exposures.

4. HIGH REPETITION-RATE

It is preferable to run a source for EUV lithography at high repetition rates.[15] The reason for this is that more pulses will be integrated in each exposure, improving the dose accuracy and by that the CD (critical dimension) control. The stability values of Fig. 3 can be taken as an example. The common source requirement[10] for the repetition rate is 5000 Hz, and the stability requirement, 3% - 3σ, is defined for this value. Assuming that the liquid-xenon-jet laser-plasma source could be operated at 25 kHz, 5 pulses would then be integrated to get 5 kHz. Then, as illustrated in Fig. 3, the equivalent coefficient of variation would be 2.6% - 1σ (7.8% - 3σ) at 50 mm, much closer to the required value of 3% - 3σ. Operating at a high repetition rate has further advantages for the dose stability since also the dose quantization is positively affected, and any spatial instability or non-uniformity is smoothened.

An important question is therefore what the maximum obtainable repetition rate of a production-scale liquid-xenon-jet laser-plasma source would be? It has previously been shown that a liquid-water-jet laser-plasma source can be operated at 250 kHz with 10% stability (2σ).[16] However, it has been argued that the situation would be different for a xenon-jet source since the jet is frozen solid rather than liquid at the point of plasma formation, and that therefore a large portion of the jet would be destroyed in the vicinity of the plasma due to, e.g., an acoustic pressure wave. However, an image of the xenon-jet directly after plasma production, Fig. 4, shows that only a small portion of the jet is affected by the laser shot. Figure 5 illustrates how the image was taken with a CCD-camera mounted on a long-working-distance microscope. The image is a double exposure where the camera shutter is opened before the laser-shot. The laser is then fired so that the plasma is registered on the CCD. A short while later, the xenon-jet is back-illuminated by another nanosecond laser pulse, resulting in a freeze-frame image of what the jet looks like just after a plasma-shot. As can be seen in the image, the jet is basically unaffected by the previous

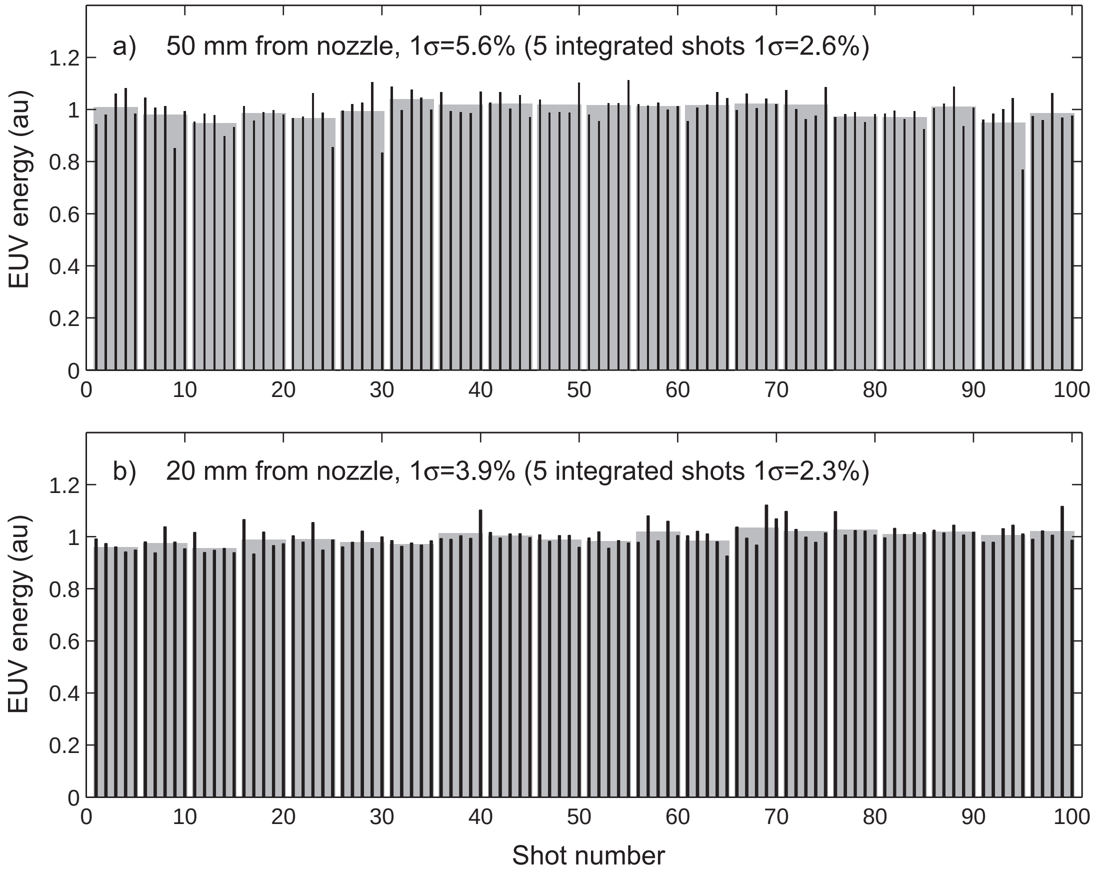

Figure 3. Diagram showing the EUV pulse-to-pulse stability when operating the plasma 50 mm (top)and 20 mm (bottom) away from the nozzle. The wide bars are five-shot averages, illustrating the gain in stability when operating at five times the repetition rate.

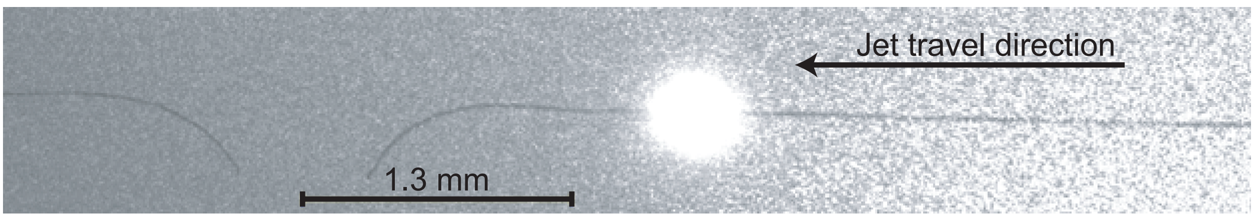

Figure 4. The image illustrates how only a small fraction of the xenon-jet is affected by a laser shot. As can be seen in the image, the jet is basically unaffected by the previous plasma at a point approximately 1.3 mm upstream towards the nozzle. Given a typical jet velocity of 50 m/s this corresponds to a maximum repetition rate of 30 kHz.

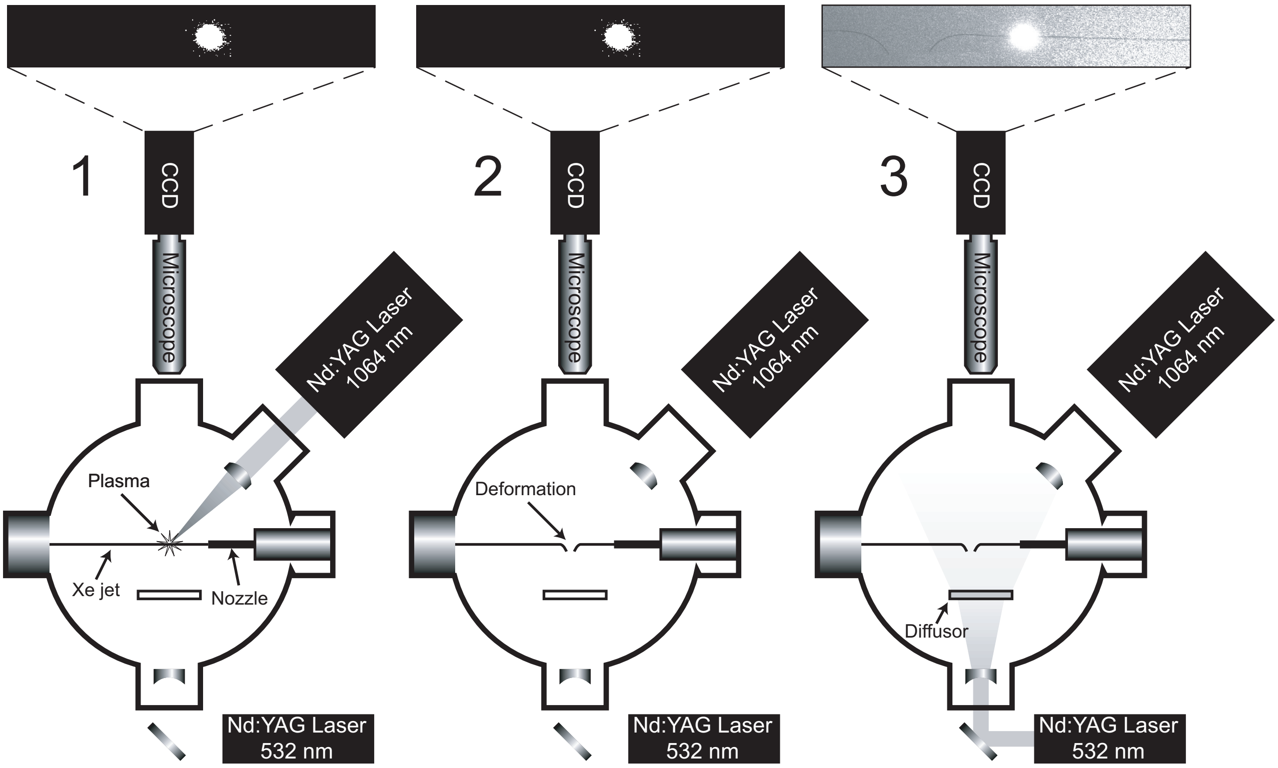

Figure 5. A CCD-camera is mounted on a long-working-distance microscope. A double-exposure image is taken by opening the camera shutter before the laser-shot, then firing the laser so that the plasma is registered on the CCD, and finally back-illuminating the xenon-jet by another nanosecond laser pulse, to get a freeze-frame image of what the jet looks like just after a shot.

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5. MIRROR LIFETIME

One of the toughest demands on a source for EUV lithography is the lifetime of the collector mirror. The collector, that will be placed about 10 cm from the plasma, is specified to have a lifetime of 1 year, or $1.6 * 10^{11}$ laser shots[17] (the lifetime being defined as the period after which the mirror has lost 10% reflectivity). Degradation of mirror performance can occur due to several reasons, and will here be classified in three categories: thermal, chemical and impact related.

The thermal issues are due to the high drive-power (up to several 10KW) needed, and are to some extent common to all source manufacturers, although high CE and large collection solid angle limit the drive-power needed as discussed above. The thermal life-time issues will not be addressed further in this paper.

The chemical issues are also to some extent common to all source techniques since they are related to the interaction between the EUV and residual gases as illustrated in Fig. 6. The EUV radiation creates secondary electrons, which dissociate the adsorbed molecules, especially hydrocarbons and water, at the mirror surface.[18] These species then react with the topmost layer, building oxide (SiOx) and carbide (SiC) layers.[19] Such contamination layers drastically reduce the reflectivity of the mirrors. 10% reflectivity loss is observed after growth of just 1 to 3 nm SiC or 0.5 to 1 nm SiOx.[20] There are however ways to prevent this contamination, including keeping an ultra-clean environment with for example the use of ultra-high-vacuum (UHV) techniques or the use of a capping layer on the mirror to reduce the reactivity[21,22] of its surface. To some extent, in-situ cleaning of the mirror[23,24] can be employed to remove the contamination, but only the carbide layers can be removed. Presently, our systems are by default equipped with UHV standard materials.

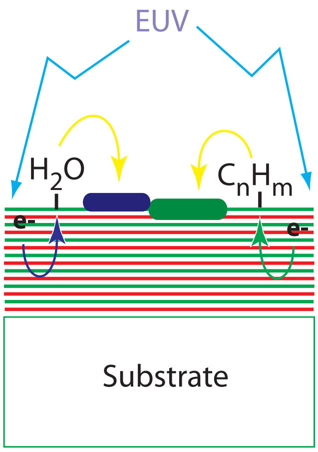

Figure 6. Simple representation of the phenomena involved in the chemical mirror-contamination process. The EUV radiation ionizes water and hydrocarbons adsorbed on the mirror surface, forming highly reactive species, resulting in the formation of carbide and oxide on the surface.

The impact related damages are the most source-specific types of degradation. Here one can discern three different types of impact damages : the ones caused by Xe fragments[25] (Fig. 7a), the ones induced by deposition/implantation of foreign materials (Fig. 7b) and the ones resulting from sputtering by hot Xe ions (Fig. 7c). In this first experiment,

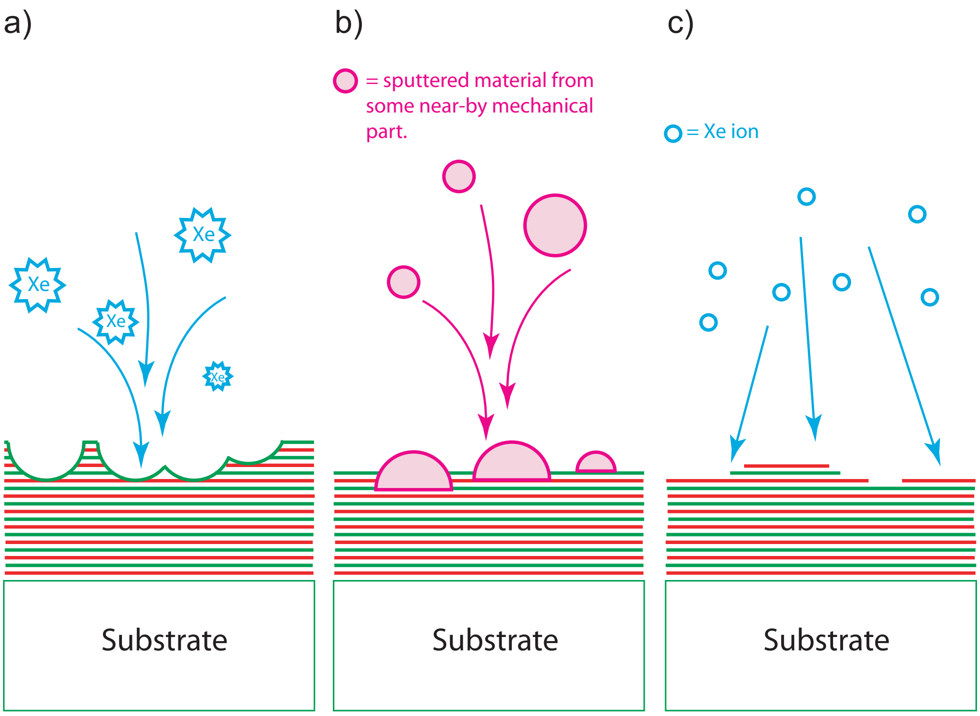

Figure 7. Schematic illustration of the processes involved during a) Xe fragment impact, b) foreign material deposition and c) Xe ions sputtering.

we mainly wanted to investigate the presence of medium/big fragment impact, looking for crater formation of 100 nm and above. As our laser-target is a solid, although microscopic, it has been argued that larger fragments, that would create impact damage, could be ejected from the region near the plasma. We exposed a Mo/Si multilayer mirror to

$\sim 10^5$ shots, about 10 cm away from the plasma, keeping part of it covered under an aluminium shield as a reference. The pressure in the chamber was in the low 10^{-3} mbar range during xenon-jet operation. Post-exposure surface analysis included Scanning Electron Microscopy and Atomic Force Microscopy. We were pleased that the results showed no evidence of fragment impact on the plasma-exposed zone. We also performed Auger analysis to check whether foreign materials were coating the surface. This was not observed, as expected from our long plasma-to-nozzle distances of 20 and 50 mm (Fig. 1). These results are very promising and are pointing at the liquid-xenon-jet source as one of the most debris-free. It is also a first indication that the liquid-xenon-jet source will not require any mechanical debris mitigation such as a foil trap,[26] or metal foils. That is especially encouraging since mechanical mitigation will induce optical obscuration and limit the available collection solid angle. Potential damage induced by highly energetic Xe ions on the mirror surface was difficult to estimate from our preliminary results. The use of an adequate background pressure is, however, believed to be an acceptable mitigation solution for energetic Xe ions. Experiments are ongoing to determine the energy distribution of the ions produced.

6. CONCLUSIONS AND FUTURE

To conclude, this paper have presented some recent improvements of the liquid-xenon-jet laser-plasma source for EUV lithography, including the ability to operate a stable plasma at a distance of 50 mm from the nozzle, the first positive mirror-lifetime results, and improved laser-to-EUV conversion efficiency of 0.75 %/(2%BW 2πsr) at λ=13.45 nm. Work will of course continue on the improvement of all aspects of the source, although especially important is the demonstration of high-power operation. Such experiments will be done in collaboration with different laser manufacturers and reported elsewhere. Further characterization of the source will also be performed in order to obtain, among other things, the spatial distribution of the EUV emission, and EUV-emission images of the plasma. Several mirror-lifetime related experiments are also planned for the near future.

7. ACKNOWLEDGEMENT

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