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Laser generated plasma sources for EUV lithography and debris mitigation issue: theoretical and experimental estimates at ENEA

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The mitigation of the debris produced by laser plasma sources is a dramatic issue for the demonstration of the feasibility of lithographic processing via extreme ultraviolet radiation. In this connection, the characterization of the emitted debris in terms of nature (ionic or cluster), sizes and mechanism of formation are of crucial relevance. The experimental investigations and the theoretical estimates performed at ENEA, in view of the development of a reliable Debris Mitigation System for EUV lithography, are presented. The thermalization length of debris of different materials (both ionic and particulate) is calculated as a function of the size and the kinetic energy of the debris, as suggested by the experimental characterization. Different buffer gases are considered in order to assess the effectiveness of their respective use.

1. Introduction

Extreme Ultraviolet Lithography (EUVL) is presently considered one of the most promising technologies to transfer images from a mask onto a semiconductor wafer with a $<100\,nm$ resolution [1]. It potentially extends optical lithography by using EUV radiation $(10\,nm - 15\,nm)$. The essential requirement for this technology is to have a reliable, clean and powerful light source at the wavelength of interest, which is presently near $13.5nm$, also displaying a conversion efficiency as high as possible. Evidently, working in the EUV spectrum poses challenges, basically due to the fact that the properties of materials in the EUV are very different from their properties in the visible and UV ranges. In fact, since EUV radiation is absorbed by all materials, even gases, a system for EUVL must be enclosed into a vacuum chamber. In addition, EUV imaging can not use refractive optical elements like lenses and transmission masks, entirely reflective optical elements being required. Finally, practical EUV sources - be they based on laser produced plasmas (LPP) or gas discharge produced plasmas (GDPP) - not only generate the desired EUV radiation but also produce debris that severely limits the lifetime of the collecting optics in the lithographic system. Indeed, decreasing debris from the source and/or from the source environment, and hence enhancing optics lifetime are the main issues that are challenging the EUVL community. In bulk solid-type LPP sources, for instance, fast ions from the plasma would significantly damage the collector mirror, which is typically located near the EUV source (Fig. 1.1), by etching and implantation of the multilayer mirror coating. Consequently, various methods for controlling the debris from plasma have been proposed: application of electric and/or magnetic fields for deflection or velocity reduction, use of appropriate ambient gas for velocity reduction, or of foil traps for particle capture as well as of mass-limited (e.g., porous) targets for reducing debris emission without affecting the conversion efficiency. Evidently, it is important to know the characteristics of the debris and to understand the debris-production mechanism in order to devise techniques and tools for debris-emission control and/or debris suppression.

The design of an efficient Debris Mitigation System (DMS) is under active consideration at the ENEA laboratory in Frascati [2]. A characterization of the debris (types

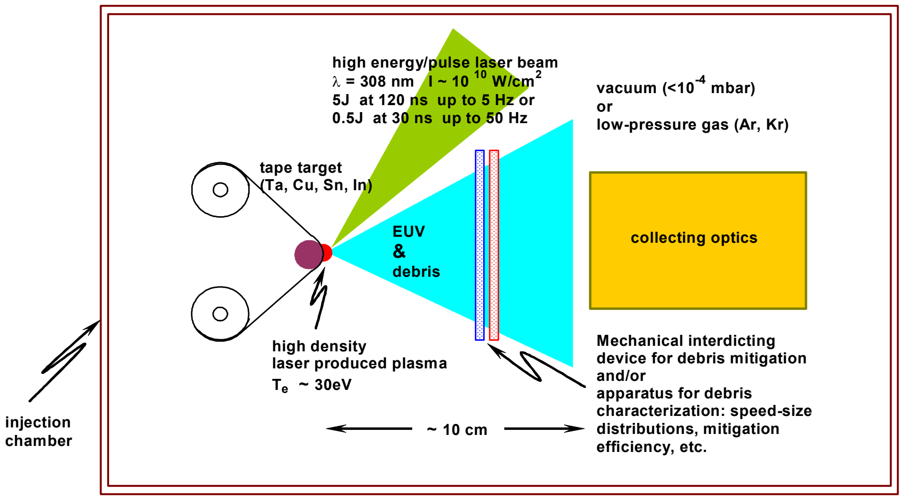


Figure 1.1: Primary elements of an LPP EUV lithographic device, basically inspired by the experimental setup implemented at the Frascati ENEA laboratory for EUV lithography and DMS related investigations.

and relative speed-size distributions) emitted by the source - a tape target irradiated by a properly focused high-energy/pulse or high repetition rate laser beam - has been performed. Different solid materials: Ta, Cu, Sn and In, and the beams from both the XeCl ($\lambda = 308nm$) Hercules (a large-volume laser developed at the Frascati ENEA laboratory) and commercial lasers are used, the respective intensities being adjusted in order to maximize the EUV emission ($I \simeq 10^{10} W/cm^2$). In general, debris from an LPP include energetic ions, neutrals and particulates. The specific measures carried out at the ENEA laboratory revealed that the atomic debris (i.e. ions and neutrals), which directly emerge from the plasma, have velocities within the range $10^4 \div 10^5 m/s$. In comparison, particulates have rather moderate velocities in the range $10^2 \div 10^3 m/s$, but larger sizes which make the gas ineffective as stopping medium.

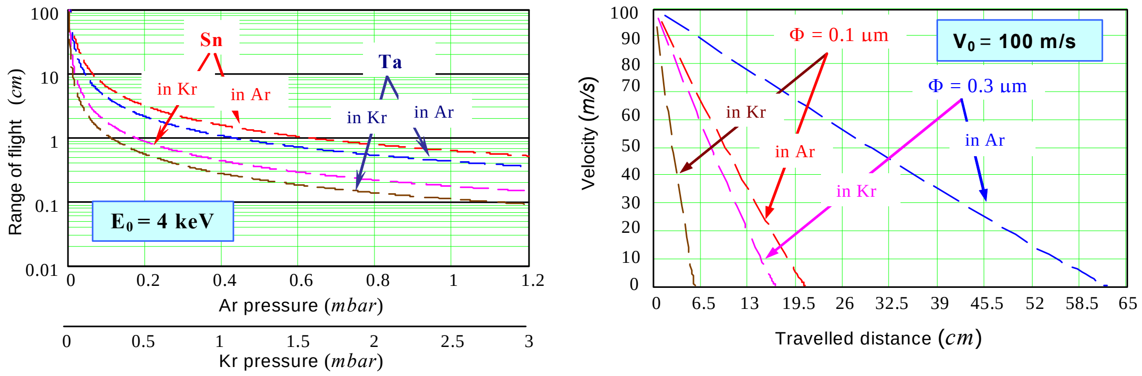
Accordingly, a combination of velocity moderating and mechanical interdicting devices has been devised as an eligible debris mitigation system. The former uses suitably chosen ambient gas under an appropriate pressure allowing for EUV transmission as high as possible ($> 80\%$) in order to significantly reduce the range of flight of the atomic debris emanating from the source. The mechanical device, whose design is under the secrecy clause of the More Moore European project, is mainly aimed at interdicting the arrival on the collecting mirrors of the particulates, which, due to their quite varied sizes (diameters $\sim 10^{-1} \div 10 \mu m$) and the mechanism for their formation are hardly moderated by the gas.

A short account of the theoretical and experimental estimates, concerning the velocity characterization of the emitted debris and the velocity moderating effectiveness of gases, like Ar and Kr, used as background, is given in Sec. 2. The crucial role of the mechanical interdicting device on stopping large-size particulates is elucidated in Sec. 3.

2. Debris velocity mitigation: effect of the ambient gas

The choice of the ambient gas is ruled by the demand for an EUV transmission as high as possible ($> 80\%$) and a velocity moderating effect as effective as possible.

When comparing the transmission curves of Argon and Krypton over the range $13nm \leq$



(a) *(b)*

Figure 2.1: *(a)* Range of flight of atomic Sn and Ta debris vs. gas pressure in Ar and Kr as predicted by Bohr's model for nuclear stopping in the considered gases. E_0 denotes the debris initial kinetic energy. *(b)* Velocity-range plots of Ta particles of different diameters Φ in Kr and Ar for an initial speed $V_0 = 100m/s$.

$\lambda \leq 15nm$, the pressure of the two gases being properly adjusted in order to assure a high EUV transmission ($> 80\%$) through all the propagation distance from the target to the collecting optics ($\sim 10cm$ in the ENEA EUVL setup, amounting to a pressure of $0.4mbar$ and $1mbar$ respectively for Ar and Kr), one sees that Ar is well transparent over all the pertinent λ-range. In contrast, Kr inefficiently transmits the EUV radiation up to $13.8nm$, at which it becomes well transparent. This behaviour has the advantage of naturally inhibiting the transmission of the undesired out-of band radiation. However, it makes Kr usable for EUVL at wavelengths out of the presently preferred band at $13.5nm$.

Being Kr ($A = 84$) more heavy than Ar ($A = 40$) and allowing as well for higher pressures, it is expected that the stopping power of Kr be higher than that of Ar, of course, under the appropriate relative pressures. This is confirmed by the trend shown in Fig. 2.1.a) of the ranges of flight of ion/neutral debris in Ar and Kr. In particular, Sn and Ta debris have been considered in the figure. The plots are based on Bohr's model for the nuclear stopping (the electronic stopping being negligible) [4]. We see that the range of flight in Kr is expected to be almost 4 times smaller than that in Ar in the relative pressure conditions of our interest.

Figure 2.1.b) shows the velocity-range plots in Ar and Kr for Ta particles of different sizes and initial velocity $V_0 = 100m/s$. In the analysis, the particle is modelled as a surface smooth rigid sphere of diameter Φ, which moving in the gas experiences a resistive force depending on its velocity relative to the gas and the gas (dynamic) viscosity and density. For the velocities and gas pressures of our concern, the Reynold number is $\ll 10^3$, thus implying an inverse law dependence of the drag coefficient on the particle velocity, and the Knudsen number indicates a free-particle regime in Ar over the range of particle sizes ($\Phi = 0.1 \div 10\mu m$), and an intermediate regime in Kr for particle diameters $\Phi > 1\mu m$.

Again, it is seen that the speed-moderating power of Kr is higher than that of Ar; in any case, however, heavy and large size particles ($\Phi \geq 1\mu m$) may be stopped, in a range compatible with a high EUV transmission, only for very low starting speed ($V_0 \ll 10m/s$).

The values of the kinetic energies and velocities used as input data in the simulations are suggested by the results of the experimental study of the debris velocity distribution. In fact, simple time-of-flight technique based measures, like those performed using an electrostatic energy analyzer or a Faraday cup, resulted in a quite varied kinetic energy

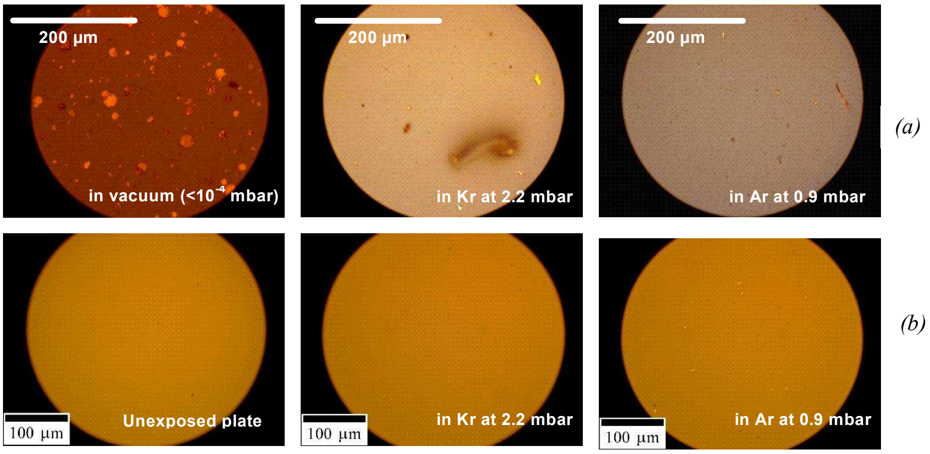


Figure 3.1: Glass sample plates, as observed at an optical microscope, after exposure to the Cu plasma debris stream in three different environmental conditions in the injection chamber. The mechanical device is active in *(b)*. Laser beam data: $\lambda = 308nm$, $E = 0.5J/shot$, $\tau = 30ns$, $I \simeq 10^{10}W/cm^2$.

distribution of atomic debris with an upper limit of $\sim 10keV$. In contrast, examination of subsequent CCD images of particulates streaming outward from the center of the laser-target interaction region, resulted into a velocity range of 10-100m/s.

3. DMS efficiency: preliminary results and conclusions

Figure 3.1.a) shows the contamination by plasma debris displayed by glass sample plates, placed at $5cm$ from the Cu target (Fig. 1.1), after being suitably illuminated (in order to maximize EUV emission) by the properly focused beam from the aforementioned commercial laser. After an exposure time corresponding to 3000 laser shots in vacuum and 10000 laser shots in gas (Ar or Kr), the plates have been observed by an optical microscope. It is evident that the suppression effectiveness of Kr is superior with respect to that of Ar, although it remains still inadequate for large-size particulates. Indeed, as shown in Fig. 3.1.b), for them the interdicting action of the mechanical device is definitely effective, even though with a still low mitigation factor (270). However, the non optimal environmental conditions of operation and the still preliminary design of the mechanical device are in favor of the final goal of producing a DMS with the mitigation factor appropriate for EUVL. Also, recent experiments have evidenced the need for a mechanism of filtering the ultra-fine particulate powder, which, formed through a rather complex mechanism of interaction with the ambient gas, by the concurrence of the mechanical device as well come to invade the injection chamber.

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