Optica Applicata, Vol. XXXVI, No. 4, 2006

Metrology of Mo/Si multilayer mirrors at 13.5 nm with the use of a laser-produced plasma extreme ultraviolet (EUV) source based on a gas puff target

R. RAKOWSKI[1], A. BARTNIK[1], H. FIEDOROWICZ[1], R. JAROCKI[1], J. KOSTECKI[1], J. KRZYWIŃSKI[2], J. MIKOŁAJCZYK[1], L. PÍNA[3], L. RYĆ[4], M. SZCZUREK[1], H. TICHÁ[5], P. WACHULAK[1, 6]

[1]Institute of Optoelectronics, Military University of Technology, Kaliskiego 2, 00-908 Warsaw, Poland

[2]Institute of Physics, Polish Academy of Sciences, al. Lotników 32/46, 02-668 Warsaw, Poland

[3]Czech Technical University, Faculty of Nuclear Sciences and Physical Engineering, Brehova 7, 115 19 Prague 1, Czech Republic

[4]Institute of Plasma Physics and Laser Microfusion, Hery 23, 01-497 Warsaw, Poland

[5]REFLEX s.r.o., Novodvorska 994, 14200 Prague 4, Czech Republic

[6]Colorado State University, Fort Collins, CO 80523, USA

In this paper an application of a recently developed laser plasma source of extreme ultraviolet (EUV) for optical measurements of optical characteristics of Mo/Si multilayer mirrors is presented. The source is based on an xenon-helium double-stream gas puff target irradiated with laser pulses from a Nd: YAG laser system ($E = 0.55$ J, $t = 3.9$ ns, $f = 10$ Hz, $M^2 = 2.5$). The results show that the source can be useful for EUV lithography technologies as a metrology tool in the semiconductor industry.

Keywords: laser-produced plasma extreme ultraviolet (EUV) source, gas puff target, Mo/Si mirrors, EUV spectroscopy.

1. Introduction

As there are no transparent optics below 100 nm of wavelength, collective and imaging optics for the future EUV lithographic tools are based on multi-layer mirrors (MLMs) [1]. The spectral window of Mo/Si mirrors at 13.5 nm is a common consensus for EUV lithography [2]. There is a strong need for proper EUV sources dedicated to metrology of EUV optics required during multi-layer fabrication. This paper directly addresses this problem. A laser-plasma EUV source based on a double stream gas puff target [3] has been recently developed [4] and successfully applied in the optical measurements of the Mo/Si multi-layer mirrors. The source has been developed in the frame of the European MEDEA+ programme, dedicated for EUV lithography technologies. In this paper the characterization research of the source (including CE, spectral, spatial and temporal measurements of EUV emission) are presented. Various diagnostic tools, namely a grazing incidence spectrograph, a pinhole camera and absolutely calibrated semiconductor detecting systems were utilized in order to characterize properties of the source. In result optimization of the source has been performed. The optimized EUV source was used to measure the reflectivity of the Mo/Si mirrors at a selected grazing angle.

2. Experimental arrangement

A schematic diagram of the experimental set-up is presented in Fig. 1. The valve system to form double-stream gas puff targets was located in the centre of the source chamber. The valve system is described elsewhere [4]. The created xenon/helium targets were irradiated with a laser beam from the Nd:YAG laser ($E = 0.558$ J, $t_{\mathrm{FWHM}} = 3.9$ ns, $M^2 = 2.5$, $f_{\mathrm{max}} = 10$ Hz) was located inside a cylindrical tube that was tightly connected to the source chamber. This solution simplifies the set-up and prevents users from laser exposures. The laser beam was focused onto the target with the use of a lens of the focal length of 50 mm mounted in the chamber window. Since it was found in previous experiments that EUV emission is very sensitive on changes of the laser focus position in respect to the gas puff target, a micromanipulator to move the valve perpendicularly to the laser beam axis was employed. The source was coupled to the experimental chamber equipped, with motorized stages for alignment of the Mo/Si mirrors to be characterized. To select EUV radiation at 13.5 nm the Mo/Si multi-layer mirror (Fraunhofer Insitute, Jena, Germany) was mounted inside the chamber between the source and the mirror under study. The mirror was set at 45° thus allowing a 33% reflectivity for 13.5 ± 0.5 nm in the 7.4% BW. The characterized Mo/Si mirrors (fabricated by Reflex s.r.o., Prague, Czech Republic) were installed inside the chamber on motorized translation and rotation stages in order to measure angular distribution of the reflectivity. Three mirrors were used, two of which were previously etched with a stream of argon for 6 and 12 minutes, respectively. In addition, the experimental chamber enabled the connection of various diagnostic instruments to measure EUV emission, such as spectrograph, pinhole camera and silicon photodiodes. A flat field grazing incidence spectrograph with the varied grooves period grating (Hitachi, average 1200 grooves/mm) equipped with a CCD back illuminated camera (Roper) was used to measure EUV spectra. A spectral resolution of the spectrograph was of the order of 0.1 Å. For spatial imaging of the plasma emitting at 13.5 nm a pinhole camera combined with the Mo/Si selection mirror was used. The camera was equipped with a platinum pinhole of 20 μm in. A pinhole was located at 54 cm from the plasma and covered with a Zr filter of 200 nm thickness, deposited on Si_3N_4 filter

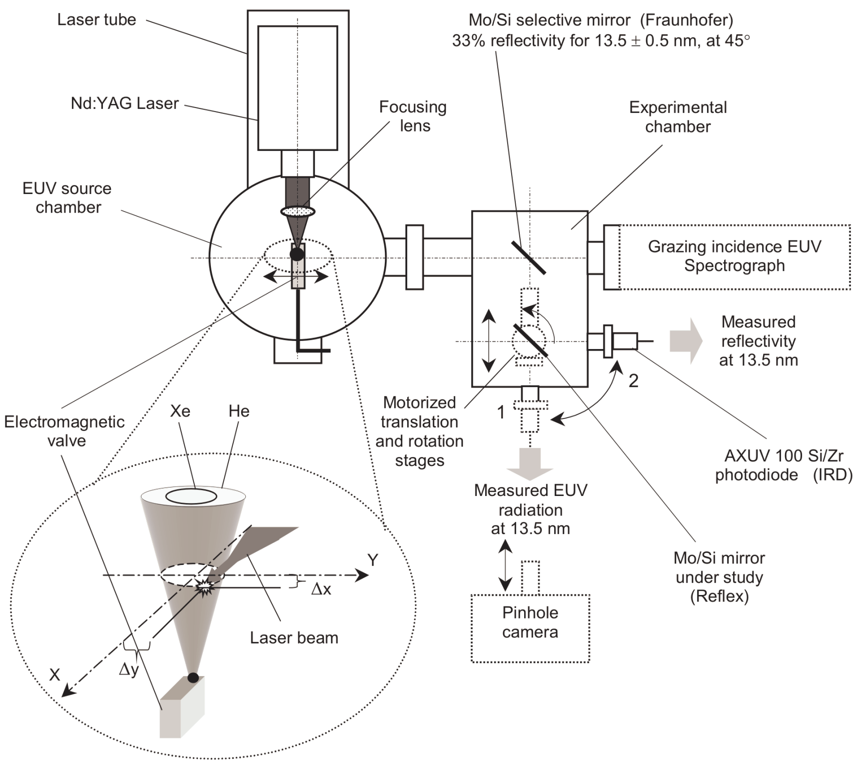

Fig. 1. Scheme of the experimental set-up used to investigate EUV optics.

of the same thickness giving a transmission of 15.4% at 13.5 nm. Because of low contrast, the magnification of about 0.4 was employed. Spatial images were recorded using a CCD camera during 60 laser shots. Absolute measurements of the EUV energy at 13.5 nm were performed with a silicon photodiode AXUV 100 Si/Zr (IRD) detection system. The detector was equipped with a 8 mm in diameter diaphragm and mounted at position 1. The same detection system was used to measure the EUV radiation reflected from the characterized Mo/Si mirror (position 2). To measure the time duration of EUV pulses a fast HS1 photodiode (IRD) equipped with the stack of Zr/Si_3N_4 filters was applied.

3. Results

3.1. Optimum source parameters

A variety of characteristics of the source were measured in series of experiments in order to obtain the input parameters of the source that lead to the optimum conversion efficiency (CE) of the laser energy into EUV energy at 13.5 nm. The following input parameters that have meaningful influence on EUV emission can be distinguished: time delay between laser pulse and opening valves, position of the laser spot in the

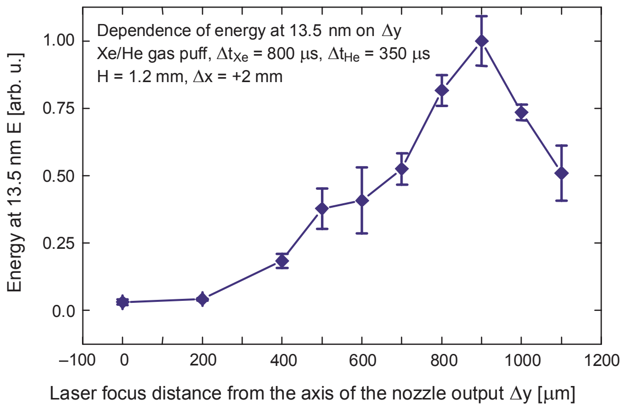

Fig. 2. Dependence of EUV emission at 13.5 nm on the distance Δy between the laser focus and the nozzle axis.

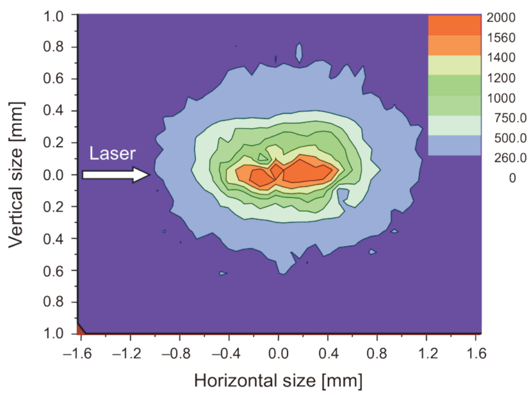

Fig. 3. Pinhole image of plasma emitting at 13.5 nm for optimum condition.

space in respect to the gas puff target and the backing pressure of the gas in the valves. The time delays for both valves which the emission at 13.5 nm is the highest were determined at Δt_{Xe} = 800 µs and Δt_{He} = 350 µs. The laser focus spot was positioned at the distance H = 1.2 mm from the nozzle output in order to prevent its thermal degradation. A 35 µm diameter laser focus was calculated using the OSLO program and confirmed experimentally. It was found that the best position of the laser spot, in order to assure the most efficient EUV production at 13.5 nm was located at Δx = +2 mm behind of the axis of the nozzle output of the valve. While the laser focus spot was located at the nozzle axis, efficient emission was shifted to the shorter wavelength, however, for the position Δx = –2.5 mm the condition were not enough for xenon ionization and plasma creation. A strong dependence of EUV emission on a shift Δy of the laser spot in the gas target perpendicularly to the laser beam axis direction was observed. It was found that to obtain the highest EUV emission the laser focus should be located in the boundary region between the xenon and helium stream [3]. Positioning the laser spots in this region of the gas target causes production of the plasma of relatively large sizes as compared to the case when the spot is inside the gas target, but EUV emission observed from this side of the gas target where plasma is created is the highest. Using the AXUV 100 Si/Zr photodiode the highest emission for $\Delta y = 900$ μm was measured. Results of this investigation are presented in Fig. 2. For the fixed optimum parameters ($\Delta t_{\text{Xe, He}}$, H, Δx and Δy), EUV emission dependence on various backing pressure in the valves was investigated. Optimum pressures of $P_{\text{Xe}} = 1.5$ MPa and $P_{\text{He}} = 0.2$ MPa were found. The maximum attainable energy of 1.6 mJ/sr at 13.5 ± 0.5 nm was calculated for optimum parameters and leads to CE of 2% within 7.4% BW per 2π sr. A pinhole image at 13.5 nm of the source for this case is presented in Fig. 3. The plasma is relatively large comparing to a plasma produced using a solid target and has a dimension of the order of 1 mm. A typical EUV spectrum recorded for the optimum parameters is shown in Fig. 4. The strongest feature belongs to an unresolved transition array (UTA) [5] and for xenon is centered at about 10.85 nm. The spectral distributions for the two values Δy are presented in Fig. 5. From spectral measurements it is clear that for $\Delta y = 800$ μm a feature at 13.5 nm was higher than in the case of $\Delta y = 900$ μm and was the strongest feature emission attainable. The following model can explain this behaviour. The increase of the Δy parameter

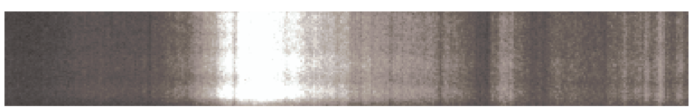

Fig. 4. Spectrum for Xe/He plasma: $P_{\text{Xe}} = 1.5$ MPa, $P_{\text{He}} = 0.2$ MPa, $H = 1.2$ mm, $\Delta x = 2$ mm and $\Delta y = 800$ μm.

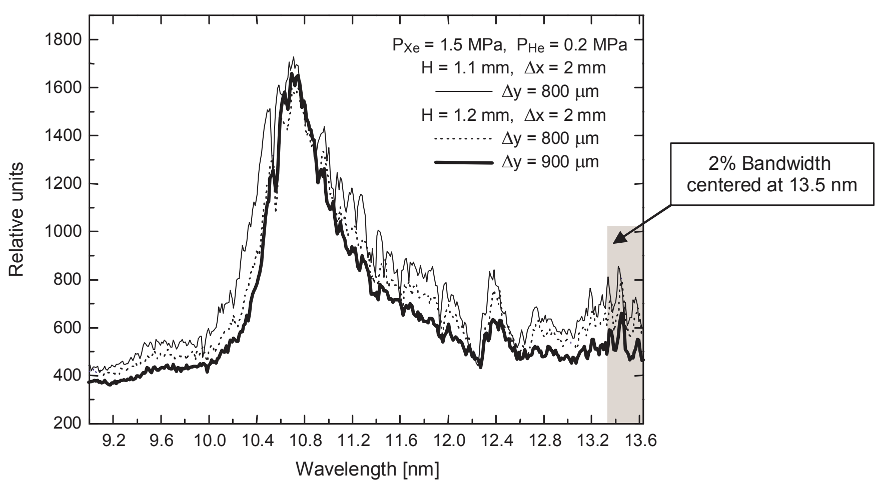

Fig. 5. Spectral distribution for the optimum condition.

significantly increases the sizes of the plasma. Moreover, in the case of the spectral measurements photons were collected only from the hottest region of the plasma, limited by a slit, while using the photodiodes photons were integrated by the whole plasma surface. For comparison, a spectrum for H = 1.1 mm at the fixed rest parameters is shown. It is seen that the peak of the UTA is unaltered while the profile width increases with Δy. The increase of Δy follows the growth of the plasma dimensions and the decrease of the electron temperature. A similar effect for a mass limited solid target was observed when the emission dependence on Sn concentration in tin reach targets was investigated [6]. The explanation of this phenomenon can be found in [7]. EUV emission at 13.5 nm which origin is from Xe XI ion stage is marked in Fig. 5 within 2% BW. It is known that the time duration of the EUV emission corresponds to the laser pulse duration. Measured with the fast photodiode HS1 (τ_{rise} = 0.25 ns), the EUV pulse had a FWHM in the range of 3.7–3.8 ns while a FWHM the laser pulse had a 3.9 ns FWHM.

3.2. Mo/Si mirrors investigation

The optimized EUV source was used in the reflectivity measurements of Mo/Si mirrors. At first, the EUV average energy for the optimum parameters at 13.5 ± 0.5 nm was

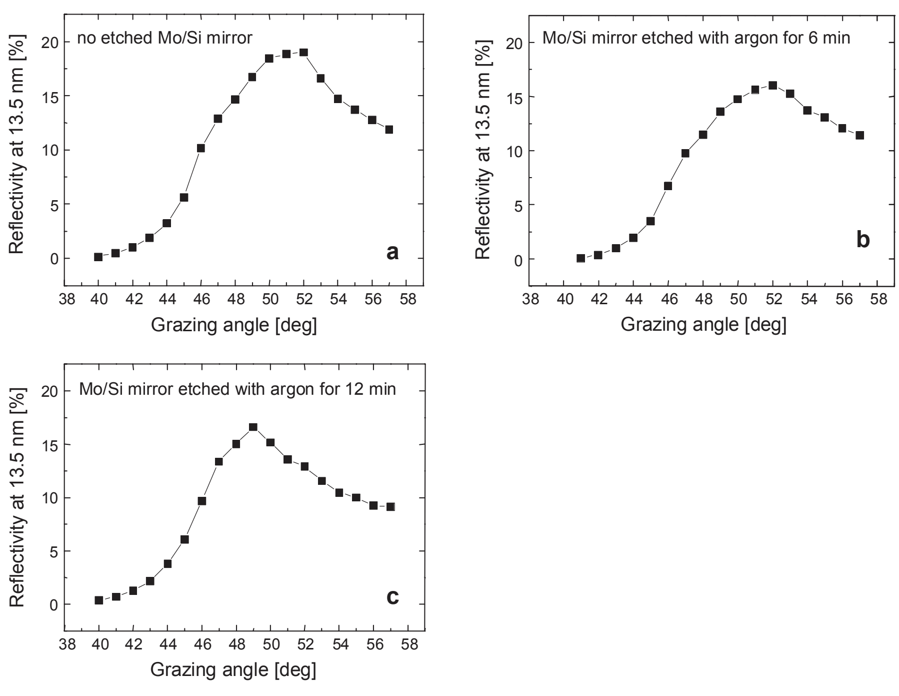

Fig. 6. Angular distribution of the reflectivity for optimum condition: no etched mirror (**a**), etched for 6 min (**b**), etched for 12 min (**c**).

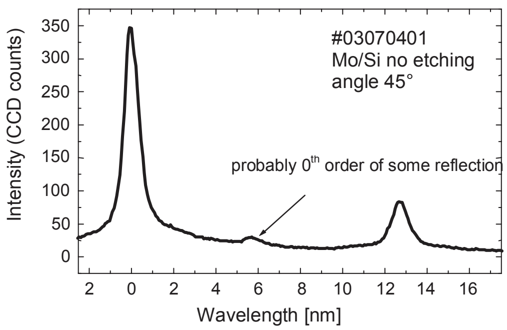

Fig. 7. Spectrum of the EUV radiation reflected from investigated Mo/Si mirror.

measured with the use of the calibrated photodiode AXUV 100 Si/Zr (Fig. 1). This yield was used as a reference energy for the reflectivity calculations. Than, the motorized stages with a mirror to be investigated were located inside the experimental chamber. The photodiode from the flange 1 to the flange 2 side was replaced, *cf* Fig. 1. The reflected emission form the Mo/Si mirror, for selected grazing angles, have been measured in a single laser shot. For each angle position at least 10 independent measurements were performed and averaged with the reflectivity being then obtained. As a result the reflectivity distributions versus grazing incidence angle are presented in Fig. 6. In the previous experiment the maximum reflectivity at 12.7 nm at 45° in the EUV region for these mirrors was found out (Fig. 7). But the maximum was predicted for 13.5 nm, because they were so optimized. Thus a peak reflectivity was not expected for the 45° grazing angle. One can see that the peak reflectivity for 52° grazing angle is in the case of no etched and for 6 min etched mirrors and for 49° in the case when mirror was etched for 12 minutes with argon. The maximum reflectivity only at the level of half that is theoretically attainable [8] for no etched mirror was reached. Moreover it is seen that diagrams are not symmetrical. Probably reasoning of all this may date back to those parameters of the mirror processing such as the layer and the inter-diffusion thickness and roughness were not successfully controlled during the deposition process.

4. Conclusions

The optimized laser plasma EUV source based on a gas puff target has been used for the characterization measurements of the Mo/Si multilayer mirror. The conversion efficiency (CE) of the laser energy into the EUV for 13.5 nm (7.4% BW in 2π sr) up to 2% for the xenon-helium gas puff target, has been measured for the optimum source parameters. The growth of CE should be possible if opacity effects are minimized (by controlling a profitable absorption/emission ratio in the plasma) [9, 10]. The angular distributions of the reflectivity of Mo/Si multi-layer mirrors (Reflex s.r.o.), were performed successfully. The results have proved a usefulness of the source for EUV metrology applications having an effect on a further development of the next generation lithography technologies.

References

[1] STUIK R., LOUIS E., YAKSHIN A.E., GÖRTS P.C., MAAS E.L.G., BIJKERK F., SCHMITZ D., SCHOLZE F., ULM G., HAIDL M., *Peak and integrated reflectivity, wavelength and gamma optimization of Mo/Si, and Mo/Be multilayer, multielement optics for extreme ultraviolet lithography*, Journal of Vacuum Science and Technology B **17**(6), 1999, pp. 2998–3002.

[2] BANINE V., MOORS R., *Plasma sources for EUV lithography exposure tools*, Journal of Physics D: Applied Physics **37**, 2004, pp. 3207–12.

[3] FIEDOROWICZ H., BARTNIK A., JAROCKI R., RAKOWSKI R., SZCZUREK M., *Enhanced X-ray emission in the 1 keV range from a laser-irradiated gas puff target produced using the double-nozzle setup*, Applied Physics B: Lasers and Optics **70**(2), 2000, pp. 305–8.

[4] FIEDOROWICZ H., BARTNIK A., JAROCKI R., KOSTECKI J., KRZYWIŃSKI J., MIKOŁAJCZYK J., RAKOWSKI R., SZCZUREK A., SZCZUREK M., *Compact laser plasma EUV source based on a gas puff target for metrology applications*, Journal of Alloys and Compounds **401**(1–2), 2005, pp. 99–103.

[5] O'SULLIVAN G., FAULKNER R., *Tunable narrowband soft X-ray source for projection lithography*, Optical Engineering **33**(12), 1994, pp. 3978–83.

[6] NAKAI M., NISHIMURA H., SHIGEMORI K., MIYANAGA N., NORIMATSU T., NAGAI K., MATSUI R., HIBINO T., OKUNO T., SOHBATZADEH F.S., TAO Y., HASHIMOTO K., YAMAURA M., FUJIOKA S., NAGATOMO H., ZHAKHOVCKII V., NISHIHARA K., UCHIDA S., SHIMADA Y., FURUKAWA H., NAKATSUKA M., IZAWA Y., *Study on EUV emission properties of laser-produced plasma at ILE, Osaka*, Proceedings of SPIE **5196**, 2004, pp. 289–97.

[7] O'SULLIVAN G., CUMMINGS A., DUNNE P., HAYDEN P., MCKINNEY L., MURPHY N., WHITE J., *Atomic physics of highly charged ions and the case for Sn as a source material*, [In] *EUV Sources for Lithography*, [Ed.] V. Bakshi, SPIE 2006, p. 149.

[8] http://www-cxro.lbl.gov.

[9] DE BRUIJN R., KOSHELEV K., KOOIJMAN G., TOMA E.S., BIJKERK F., *Absorption of EUV laser plasmas generated on xenon gas jets*, Journal of Quantitative Spectroscopy and Radiative Transfer **81**(1), 2003, pp. 97–105.

[10] FIEDOROWICZ H., BARTNIK A., SZCZUREK M., DAIDO H., SAKAYA N., KMETIK V., KATO Y., SUZUKI M., MATSUMURA M., TAJIMA J., NAKAYAMA T., WILHEIN T., *Investigations of soft X-ray emission from a gas puff target irradiated with a Nd:YAG laser*, Optics Communications **163**(1–3), 1999, pp. 103–14.

Received January 30, 2006
in revised form January 30, 2007