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High power gas-discharge and laser-plasma based EUV sources

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ABSTRACT

In this paper we discuss new results from investigations on high power EUV sources for micro-lithography based on gas discharge produced plasmas and laser produced plasmas. The EUV development is performed at XTREME technologies GmbH, a joint venture of Lambda Physik AG, Göttingen, and Jenoptik LOS GmbH, Jena.

For gas discharge EUV sources we report data based on Xenon filled Z-pinches. Prototypes of the EUV source achieve an EUV output power of 10 W in-band in continuous operation. Repetition rates of 1 kHz are possible with liquid cooling of the discharge head. The spectral distribution of the EUV radiation shows a maximum around 13.5 nm and matches the reflection characteristics of silicon/molybdenum multilayer mirrors. Conversion efficiencies between 0.25% and 0.7% into a solid angle of 2π sr were achieved with the Z-pinch source depending the discharge geometry. The total EUV average power in the spectral range between 5 nm and 50 nm is about 200 W in 1.8 sr. Pulse energy stability data show standard deviation between 1-4 %. Spatial and temporal emission characteristics of the discharge source in dependence on the discharge geometry are discussed.

The laser plasma investigations are performed with an experimental setup consisting of a diode pumped laser system coupled to a liquid jet target. Since the conversion efficiency into EUV-power depends critically on the emitter density in the interaction region, we use a Xenon-jet, which is cryogenically liquefied and injected under high pressure into the vacuum vessel. Thus the laser is impinging on a target of solid-state density, which allows the generation of EUV-radiation with high conversion efficiencies of 0.5 % into a solid angle of 2π sr.

Keywords: gas-discharge, z-pinch, laser-produced plasma, EUV, lithography

1. INTRODUCTION

Next generation lithography exposure tools for semiconductor chip manufacturing are expected to be based on extreme ultraviolet (EUV) technologies. Current approaches of the optical system are designed to use an illumination wavelength of 13.5 nm. The mirrors used in the illumination system will reflect a spectral portion of 0.27 nm of the radiation from the EUV source (2% bandwidth).

Currently two different kinds of EUV sources are under investigation worldwide for commercialization of EUV related technology: Gas discharge produced plasmas and laser produced plasmas. The output power of the EUV radiation and source lifetime of state of the art EUV sources are the most critical parameters. Up to now they are still orders of magnitude below those parameters, which are expected as the requirements of sources for EUV-lithography mass-production. Based on current knowledge both concepts, gas-discharge sources or laser-plasma sources, have their own, specific advantages and drawbacks. Scientists at XTREME technologies are investigating both source concepts to fulfill the source requirements. The gas discharge based sources are aimed to match the specifications needed during the development phase for EUV lithography, whereas the achievement of specifications for production tools is a high technical risk. The laser produced plasma source is considered as a backup development for high EUV output power for production tools. This technology suffers from the high cost of ownership caused by the high power laser system.

Critical issues limiting the lifetime of the sources are the strong plasma wall interaction, which leads to sputtering effects and wall material erosion. In case of gas discharge produced plasma sources these are the electrodes and the

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ceramics separating them, in case of the laser produced plasma sources the nozzle providing the target material is the part closest to the plasma. Gas-discharge produced plasma sources operate with small plasma-wall separation which implies limitations due to heat removal. Laser-plasma sources offer a potentially larger plasma-wall separation while the reliable operation of the plasma at a large distance from the nozzle at a high power level has to be demonstrated. Both concepts are currently investigated by XTREME technologies.

2. GAS-DISCHARGE PRODUCED PLASMA EUV-SOURCE

We report data from gas discharge EUV sources based on Xenon filled Z-pinches [1]. A wide field of discharge parameter is accessible with this setup. This includes geometrical parameter (e.g. electrode distance, insulator diameter and electrode shapes) as well as electrical parameter (e.g. voltage, capacity and inductivity) to achieve highest conversion efficiencies (schematic see figure 1). The electrical circuit including magnetic compression stages are matched to the discharge unit to achieve short discharge current rise-times and to minimize losses in the circuit. The capacitor storage bank allow for electrical input energies up to 40 J/pulse.

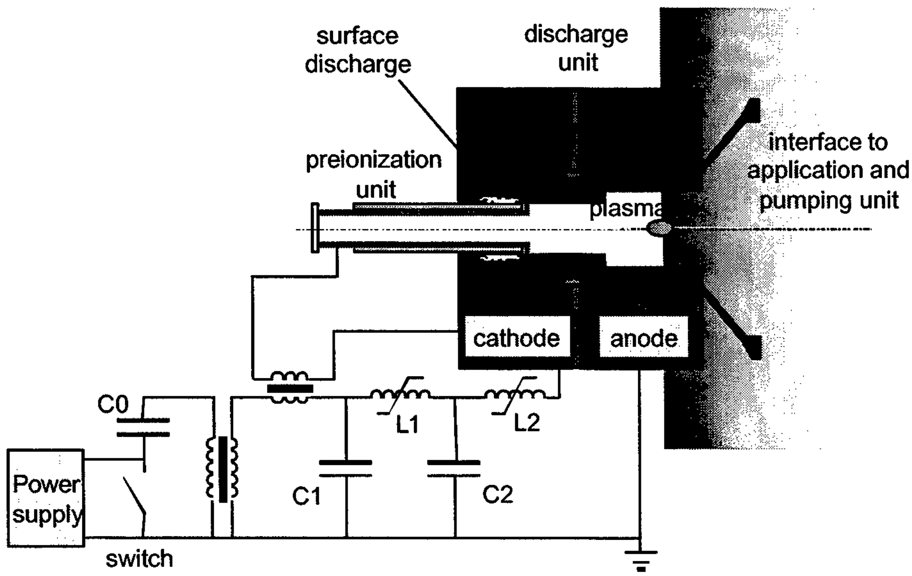

Figure 1 Schematic of the Z-pinch gas discharge device with surface pre-ionization.

The emission power of the gas discharge based source has been determined by using calibrated standard metrology tools. The energy monitoring tool comprising two multi-layer mirrors to select the proper EUV band, a metal filter to reject "out of band" radiation, and an EUV sensitive photodiode. A calibration factor is applied to account for the slightly wider EUV band of our particular measurement tool. These tools enable the absolute measurement of the EUV output power. The calibration of the measurement tools was performed in collaboration with AIXUV, Aachen, Germany. For this cross calibration the used metrology tools were compared to tools, which were calibrated before by using synchrotron radiation at PTB in Berlin.

The gas discharge prototype source achieves an EUV output power of 10 W at 13.5 nm wavelength in 2 % bandwidth and the usable angle of 1.8 sr working with a repetition rate of 1000 Hz. Assuming an isotropic emission distribution this corresponds to an output power of 35 W into a solid angle of 2π sr. Using a fast photodiode behind the described optical filters the emission duration was determined to 180 ns (FWHM). The measured output energy leads to conversion efficiencies between 0.25 and 0.7 % in 2% bandwidth and 2πsr solid angle from electrically stored energy into usable in-band EUV power, depending on the discharge geometry.

The surface discharge pre-ionization in the design allows for homogenous ignition conditions of the plasma yielding reproducible results and good pulse-to-pulse energy stability (measured between $\sigma = 1$ % and $\sigma = 4$ %) of the emitted pulses (figure 2).

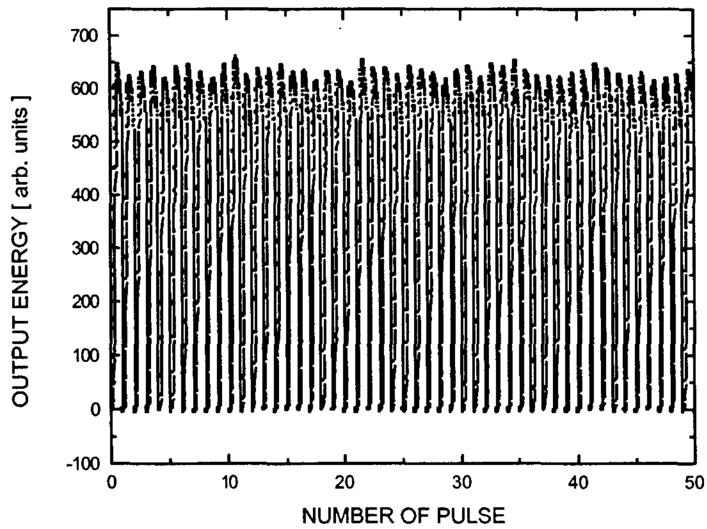

Figure 2 Pulse to pulse stability of the EUV emission. At 400 Hz repetition rate the energy emission was measured to $\sigma < 2$ %.

The emission spectrum of the radiation was measured with a reflection grating spectrograph including a flat-field grating and a CCD detector. Using Xenon as working gas the spectrum shows a maximum of intensity around 13.5 nm in adaptation to the reflection characteristic of a molybdenum silicon multilayer mirror (figure 3). The reflection band of 2% bandwidth of a multilayer system is shown as a bar in the background. Oxygen as working gas was used for the emission of small freestanding lines for the wavelength calibration and the determination of the spectral resolution of the spectrograph. Assuming delta shaped emission lines from oxygen the spectral resolution of the spectrograph could be measured to $\lambda/\Delta\lambda \approx 100$.

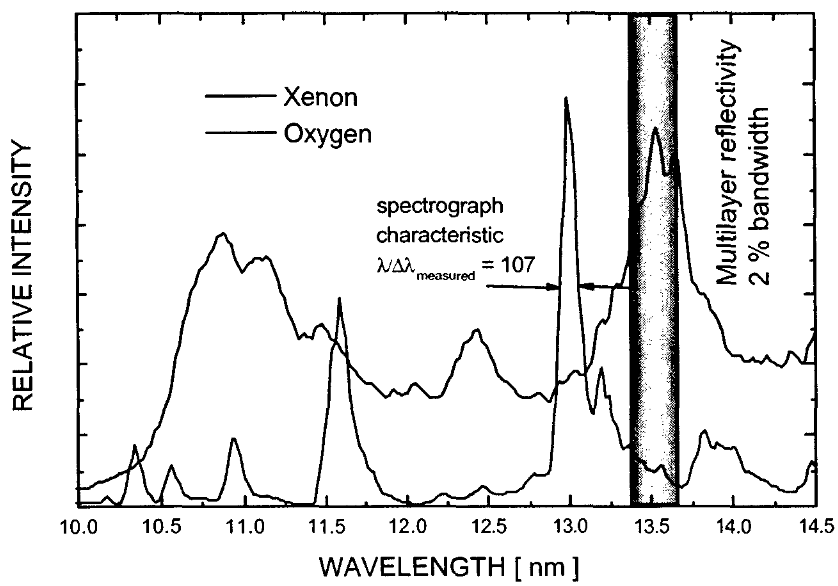

Figure 3 Emission characteristic of the Z-pinch EUV source filled with xenon in comparison to oxygen. The 2 % bandwidth of a multilayer system at 13.5 nm is shown as bar in the background.

The Xenon emission spectrum (figure 3) shows a large amount of radiation in the EUV spectral range outside of the bandwidth of 2 % around 13.5 nm wavelength. Only radiation within the bandwidth, which is marked in the spectrum, can be reflected by a stack of multilayer mirrors used for imaging in future lithography tool. All other radiation is absorbed inside the mirror layers and heats the optics. The use of grazing incidence optics with broad reflection characteristics could make this radiation utilizable for applications requiring broadband radiation as e.g. material research or micro machining.

3. LASER-PRODUCED PLASMA EUV-SOURCE

Figure 4 shows the principal setup of a laser-produced plasma EUV-source and an additional EUV optics to collect the emission and re-direct it into an intermediate focus. A similar scheme can be expected when the laser-produced EUV-plasma is employed as the source in a lithography scanner. Several diagnostics of the emission characteristics, radiative and particulate, are employed for optimization and source monitoring.

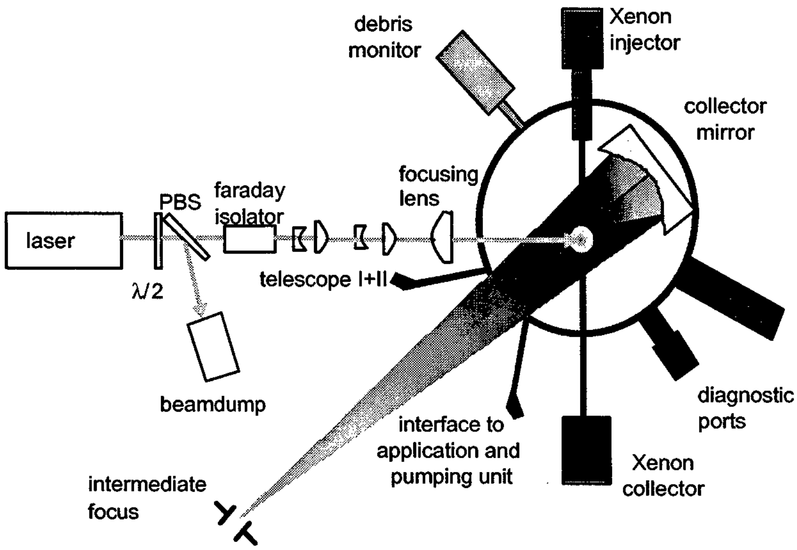

Figure 4 schematic of a laser-produced plasma EUV-source unit

Laser radiation is converted into EUV in a hot plasma with temperature T ~ 10^6 K, which is formed by the interaction of the laser beam with a high density target. Apart from the requirement of high conversion efficiency into EUV-radiation additional constraints are imposed by minimized particle-bombardment (debris) of surrounding optics.

The requirements onto the target can be summarized as follows:

(1) A volume of high target density at the laser focus to supply a large number of emitters ⇒ liquid or solid modification
(2) An interaction region at a large distance from surrounding components to minimize the heat load density at these components ⇒ high pointing stability of the target stream
(3) A benign material which converts laser radiation into EUV efficiently ⇒ Xe

The inert gas Xenon seems currently the best compromise of intense EUV-emission into a 2% bandwidth at 13.5 nm and minimal optics contamination / damage.

A first experimental setup of a laser produced plasma EUV source was built up consisting of a Xe-jet-target coupled to a pulsed 40 W laser with 100Hz repetition rate. This system was used to acquire data on the spatial stability of the jet-target and on the conversion efficiency.

Jet-targets of different liquids coupled to intense laser beams are published to generate radiation in several spectral regions, some of them covering the relevant EUV-band [2]. In our setup Xenon is cryogenically liquefied and injected under high pressure through a nozzle of several 10 μm diameter into the vacuum vessel. A 2nd cryogenic pump serves as the collector of the target material, and pumps the chamber to a pressure below 10^{-3} mbar. A photograph of the target assembly is shown in figure 5. The jet enters the chamber from the top and is collected in the cryogenic pump at the bottom. The laser beam enters the chamber normal to the plane of the figure and hits the jet in the center of the chamber.

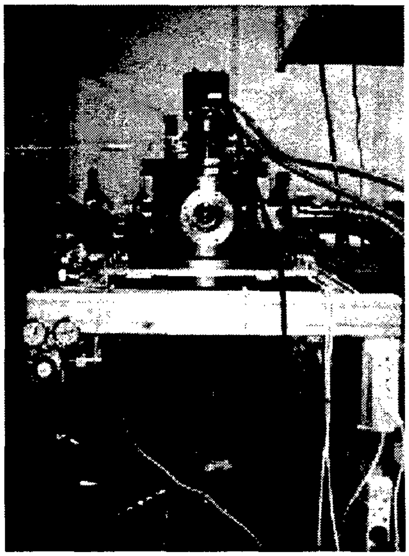

Figure 5 photograph of the interaction chamber

The spatial stability of the jet allows for plasma generation up to a distance of 1cm from the nozzle-tip. Typical experiments were performed at a distance of about 5 mm, which results in reduced fluctuations of the EUV-yield.
Figure 6 shows a photograph of the liquid Xe-jet and of the plasma generated by interaction of the laser beam with the jet respectively. The plasma picture was taken with a CCD-camera, which was sensitive in the VIS region.

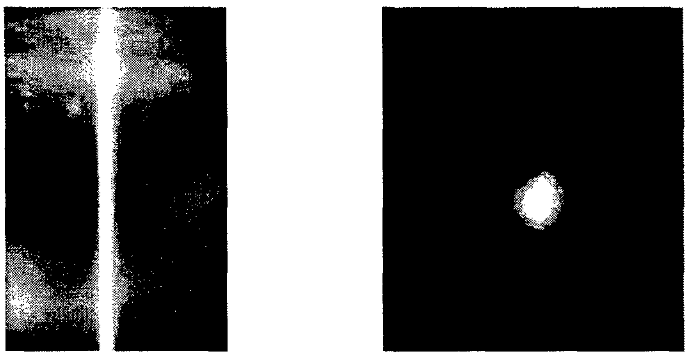

Figure 6 photograph of the liquid Xenon jet (left) and of the laser plasma generated on the jet (right)

The EUV energy was measured with a calibrated energy monitoring tool as used for the gas discharge produced plasma EUV sources and described above. Figure 7 shows an EUV energy monitor signal averaged over 128 shots. The measured EUV-yield corresponds to a conversion efficiency exceeding 0.5% in 2π sr and 2% bandwidth. The current conversion efficiency corresponds to an average EUV power of 200 mW, which can be generated with 40 W laser power.
It is noteworthy that the current conversion efficiency was obtained with alignment of the laser focus relative to the Xe-jet only. Improvements are expected by optimization of laser and target parameters.

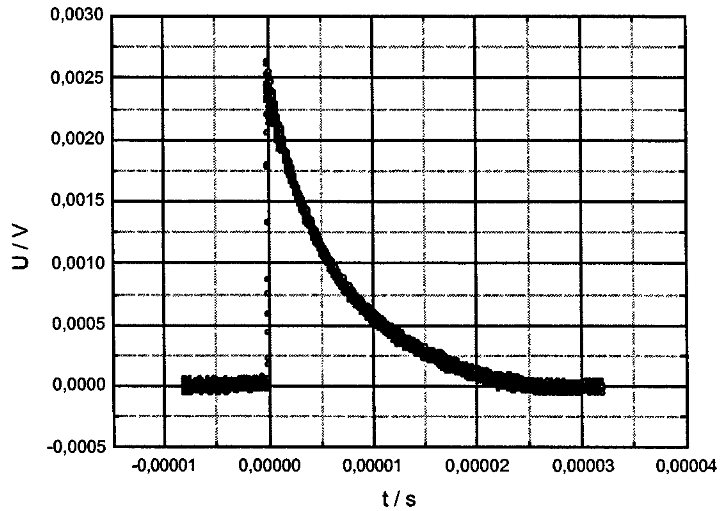

Figure 7 detector signal of the EUV-monitor averaged over 128 shots

A higher power EUV-system is currently under development, which will employ a 500 W laser coupled to an improved target injector. Figure 8 shows a CAD drawing of the complete system comprising the laser, a beam delivery unit, and the target vessel. The high power laser is based on commercially available oscillator and amplifier modules today used in industrial applications as laser machining and micro-machining. In current development status the laser driver delivers pulses of 20 ns duration at 2kHz repetition frequency at an average power of 200 W. The laser produced plasma EUV source is expected to generate an average power of 2.5 W in 2π sr and 2 % bandwidth.

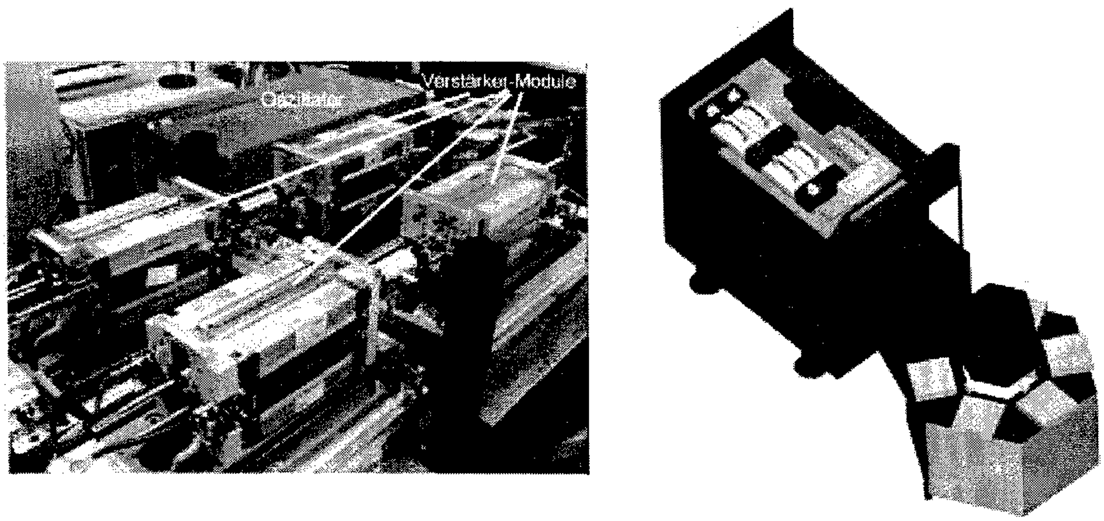

Figure 8 photograph of the high power laser (left) and CAD drawing of the laser-plasma EUV-source, employing a pulsed 500 W laser (right)

4. CONCLUSIONS / SUMMARY

EUV sources based on gas discharge produced plasmas as well as laser produced plasmas have been investigated as potential sources for EUV lithography exposure tools. For gas discharge produced plasmas conversion efficiencies of 0.3-0.7 % into 2 % bandwidth at 13.5 nm and in a solid angle of 2π sr have been measured. For laser produced plasmas conversion efficiencies under same conditions of 0.5 % have were achieved. As the conversion efficiencies are of the same order of magnitude, the generation of a certain output power requires a similar energy input into the plasma for both concepts. While the gas discharge produced plasma EUV sources require high voltage power supplies as driver, laser produced plasma EUV sources have to use laser drivers of the same average power. With gas discharge we generated an EUV output power of 10 W at 13.5 nm wavelength in 2% bandwidth. The usable angle was 1.8 sr. With the laser produced plasma we achieved 200mW EUV output power in 2π sr and 2% bandwidth.
Due to the broad emission characteristics of Xenon plasmas generated by both described methods, the output power of the sources is much higher if the useable spectral range is not limited by multilayer optics. This can be used for other applications working with broadband optics, e.g. grazing incidence mirrors.

5. ACKNOWLEDGEMENT

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