Laser-produced plasma source development for EUV lithography

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ABSTRACT

We are developing a CO_2 laser driven Tin plasma EUV source for HVM EUVL. This approach enables cost-effective EUV power scaling by high-conversion efficiency and full recovery of Tin fuel. The RF-excited, multi 10 kW average power pulsed CO_2 laser system is a MOPA (master oscillator power amplifier) configuration and operates at 100 kHz with 20 ns pulse width. The EUV light source is scalable to in-band 200 W IF power with a single 20-kW CO_2 laser beam. EUV chamber is kept uncontaminated by using a small size droplet target and effective Tin exhaust by magnetic plasma guiding. Characterization of the plasma flow in uniform magnetic field was studied by monitoring the motion of Tin plasma stream in a large vacuum chamber, depending on the magnetic flux up to 2 T. Topics relevant for HVM source is reported on continuous operation and Tin vapor evacuation.

Keywords: EUV light source, laser produced plasma, CO_2 laser

1. INTRODUCTION

CO_2 laser produced Tin plasma is the final solution as the 13.5nm light source for extreme ultraviolet lithography (EUVL). One of the technical challenges is the requirement of high average in-band power at the intermediate focus[1], together with the cleanness of the plasma chamber. Theoretical[2] and experimental[3] data have clearly demonstrated the advantage of the combination of a CO_2 laser wavelength with Tin plasma to achieve high conversion efficiency from laser pulse energy to EUV in-band energy. High average laser power due to high amplification efficiency and superior beam quality is readily available by a short pulse CO_2 laser technology.[4] The CO_2 drive laser is based on industrial high average power cw CO_2 laser modules.

The remaining technical challenge is full evacuation of injected Tin from the active volume. LPP EUV source system includes a CO_2 drive laser, a Tin droplet target supply, and a magnet for plasma guiding to fully recover the injected fuel. The Tin droplet injector is operated by continuous jet method. Precise positioning of Tin droplet was achieved by active feedback control. Magnetic plasma guiding was characterized by monitoring plasma current and shape in a large vacuum chamber with a maximum magnetic flux density up to 2 T. It was shown that Tin plasma flow was kept stable along the magnetic field line with a diameter less than 10mm to the Tin collector.

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2. COMPONENT TECHNOLOGIES OF CO_2 LASER DRIVEN TIN EUV SOURCE

2.1 Improvement of high repetition rate CO_2 laser system

Carbon dioxide laser is the most matured high power laser technology in industrial applications, in terms of robustness and reliability, as well as low initial and operational cost. RF-excitation is the commonly employed scheme in axial flow or diffusion cooled slab or waveguide configurations, allowing high repetition rates in pulsed operation by a well designed amplification system, for high repetition rate plasma generation.

We have been developing a short pulse CO_2 MOPA (Master Oscillator Power Amplifier) laser system with 20 ns pulse width and 20kW average power at 100 kHz repetition rate. Figure 1 shows the present laser system configuration. The system consists of a short pulse high repetition rate oscillator and multi-stage cascade amplifiers. The oscillator laser is a Q-switched, 20 ns, single P(20) line, RF pumped waveguide CO_2 laser with 60 W average power. The repetition rate can be tuned from 10 to 140 kHz. Commercial CW CO_2 lasers are used as amplifiers after some modification, for example, the replacement of the cavity mirrors to windows. The laser system is operable from low duty mode (2%) to full duty mode (100%), to supply driver power to the target depending on the EUV source operation.

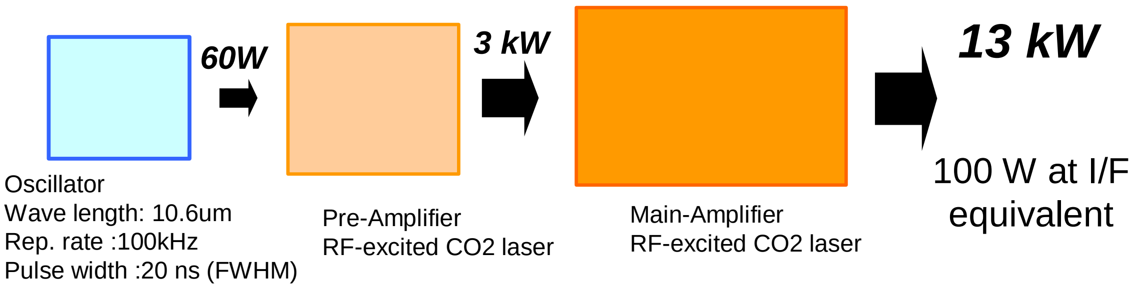

Fig.1. Configuration of the CO_2 MOPA system.

Parasitic oscillation and optical coupling between amplifiers can be eliminated after careful optimization of the beam propagation. A power meter was placed behind the final amplifier and no signal was detected during maximum RF-pumping of all amplifiers without input laser power. A well designed inter stage isolator can prevent pedestal and tail of the seed laser pulse. Figure 2 shows the temporal laser pulse profile of the amplified output. Pulse duration was 20 ns (FWHM) and the pedestal component was confirmed as less than 10% of the total output power. The real pulse energy was more than 100 mJ in this case. There is quite low beam distortion in the active gas medium during amplification, but the thermal deformation of the solid optical components inside the beam delivery system, is the main resource of the beam quality degradation. Careful cooling and optimization of the material reduced these effects. Figure 3 shows the measured beam profile at full power operation with beam quality as M^2 1.1.

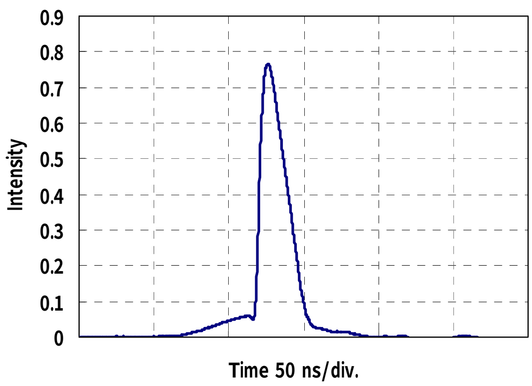

Fig.2 Temporal laser pulse profile

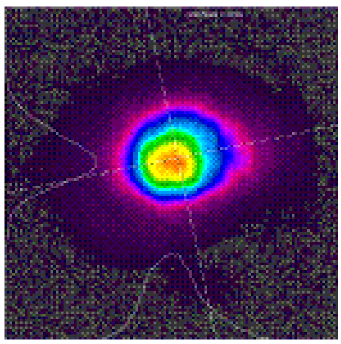

Fig.3 Spatial laser beam profile

Long term operation of the driver laser is the initial requirement in the actual EUV source. The laser system was operated at 30% duty for one hour without any degradation of the beam parameters. The average power fluctuation was less than 1% during operation. The net laser power was 3.4 kW in this case, corresponding to 11.3kW peak average power. Figure 4 shows the result of the experiment. Further optimization is now in progress to achieve 100% duty operation by optimization of laser optics in main amplifiers and focusing components.

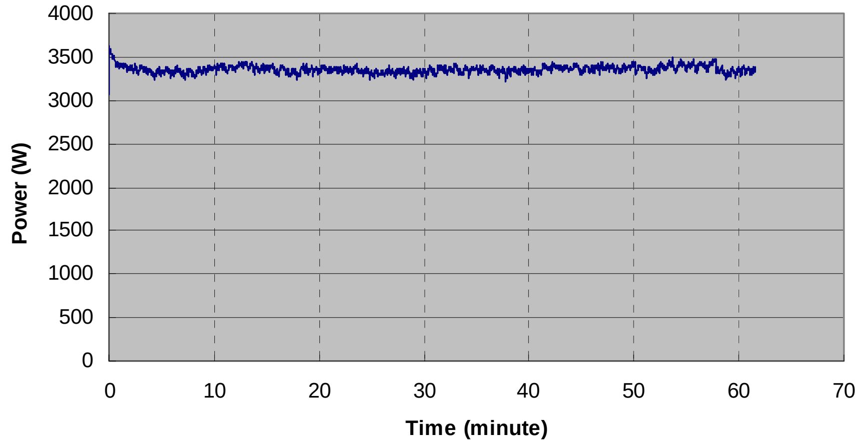

Fig.4 Long term operation of CO_2 laser at 30% duty

2.2 Stabilization of Tin droplet injector

Tin droplet is the best target for CO_2 laser produced plasma for its minimum mass and electric isolation.[5] Tin droplets with various diameters and spacings are generated by changing the nozzle inner diameter and PZT frequency. Generated minimum droplet diameter was 20 μm at 500 kHz with 20 m/s injection velocity. Long term stability of the droplet is another factor to guarantee the long term EUV IF power stability. Its spatial and temporal precision was improved by active feedback technique.

Figure 5 and 6 shows the measured results of the droplet positioning precision in spatial and temporal phase. The Tin supply tank was heated above the melting temperature of Tin, i.e. 232 °C. The liquid Sn jet was emitted from the nozzle by pressurizing the supply tank. A uniform droplet train was generated by inducing periodic disturbances on the jet surface via a PZT oscillator. The droplet size and spacing were 60 μm and 180 μm, respectively, with 400 kHz PZT driver frequency and 30 m/s injection speed. Behavior of the droplet injection is usually not stable due to fluid dynamic fluctuation. Further stabilization was achieved by an active feedback of the injector controller. The measurement was at 100 mm from the nozzle.

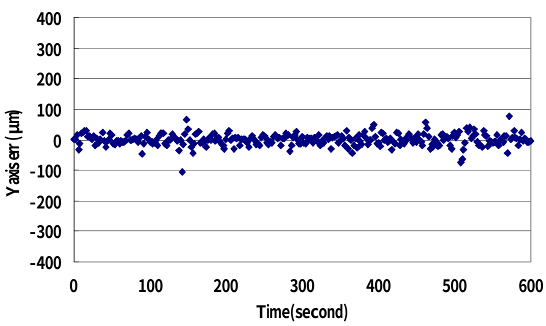

Fig. 5 Stabilization of droplet spatial precision

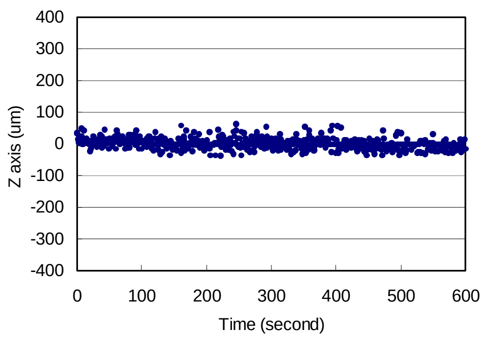

Fig. 6 Stabilization of droplet temporal precision

2.3 Characterization of plasma flow in uniform magnetic field

One of the most important requirements is full Tin recovery from the EUV plasma chamber, to extend collector mirror lifetime. Tin deposition of only 1 nm layer on a EUV collector mirror, i.e. a few atomic layers, reduces the mirror reflectivity by 10%, which is considered as the mirror lifetime specification. Injected Tin has to be fully removed from the active region in order to prevent deposition (evaporated material, molten droplets, slow ions), erosion (fast ions), and implantation (ultra fast ions) on the collector mirror.

CO_2 laser has an advantage in terms of plasma generation than a Nd:YAG laser for this purpose. The amount of neutrals from the CO_2 laser plasma was estimated to be 0.1% of the Nd:YAG laser produced plasma. We previously reported on Tin micro particles from Nd:YAG laser (1064 nm) and CO_2 laser (10.6 µm) driven plasmas using bulk Tin-plate targets and gold (Au) coated quartz crystal microbalances (QCM).[6]

A large volume superconducting magnet was employed to characterize the plasma stream in uniform magnetic field. The magnet has a vacuum chamber of 600-mm diameter placed inside the magnet bore. The magnetic flux density at the plasma point was 2 T at maximum. The experiment was performed with a Tin plate target and a Nd:YAG laser. A Nd:YAG laser pulse was 50 mJ pulse energy and 5 ns duration with the irradiated laser intensity up to 1.6 x 10^{11} W/cm^2.

Figure 7 shows a typical visible image of the plasma flow from the Tin plate target, taken by a CCD camera at time delay 2 µs after EUV emission. Characterization of the plasma flow was performed to study the detailed mechanism of the phenomena, depending on the irradiation intensity and magnetic flux density. Figure 8 shows the experimental configuration of the ion current measurement. A large diameter (44 mm) Faraday Cup was installed on the beam pass of the plasma flow at 200 mm to 300 mm from the plasma generation position. Figure 9 shows the measured plasma current waveform without and with magnetic field. It was observed that the plasma current increases its pulse duration to 20 µs and peak current to 5A with magnetic filed. Total charge was up to 0.1mC. The laser irradiation intensity was 10^9 W/cm^2 in this case. It is also important to evaluate the plasma flow dynamics. Figure 10 is the experimental setup to observe the cross section of the plasma flow. A phosphor screen was installed 45 degree onto the beam pass of the plasma stream. Figure 10 is the measured beam spatial shape. Plasma stream comes from left hand side, and non uniform shape was observed. It was indicated that some plasma instability like Rayleigh-Taylor instability or exchange instability might exist in the partially ionized plasma stream. The plasma diameter was less than 10mm on the screen, which was enough small to be collected by a Tin recovery device.

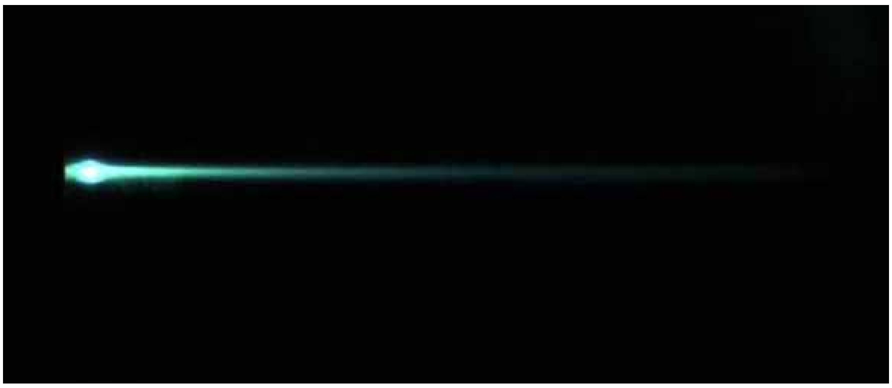

Fig.7 Visible image of plasma flow with 2 T

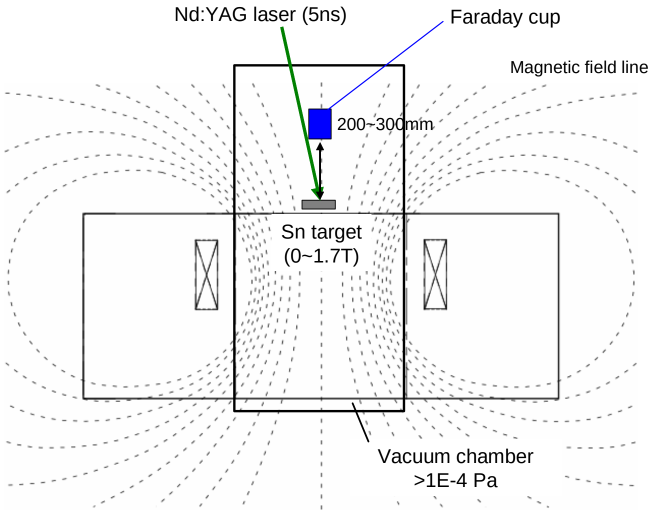

Fig.8 Experimental setup for ion current measurement

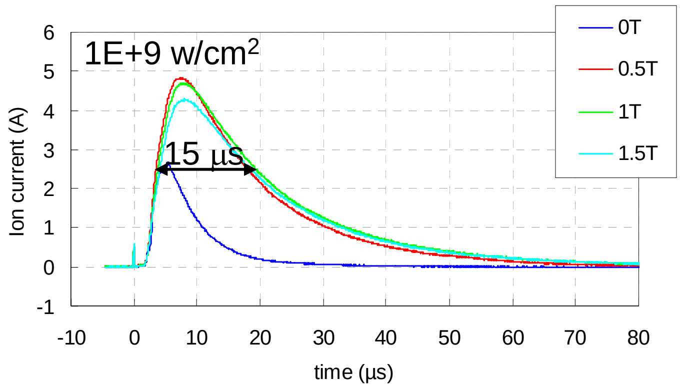

Fig. 9 Measured ion current pulse shape

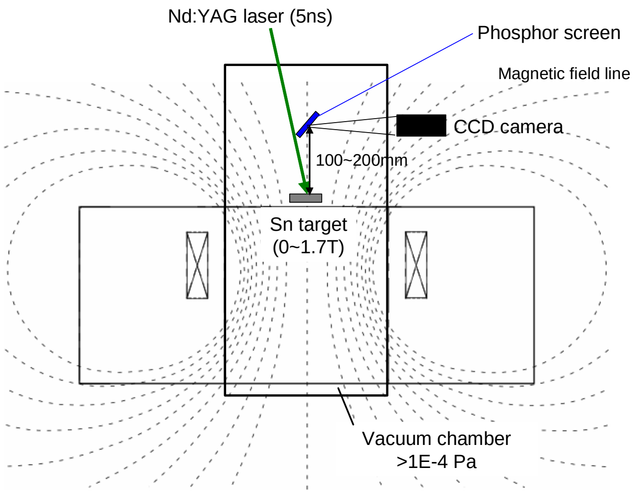

Fig. 10 Experimental setup for beam shape measurement

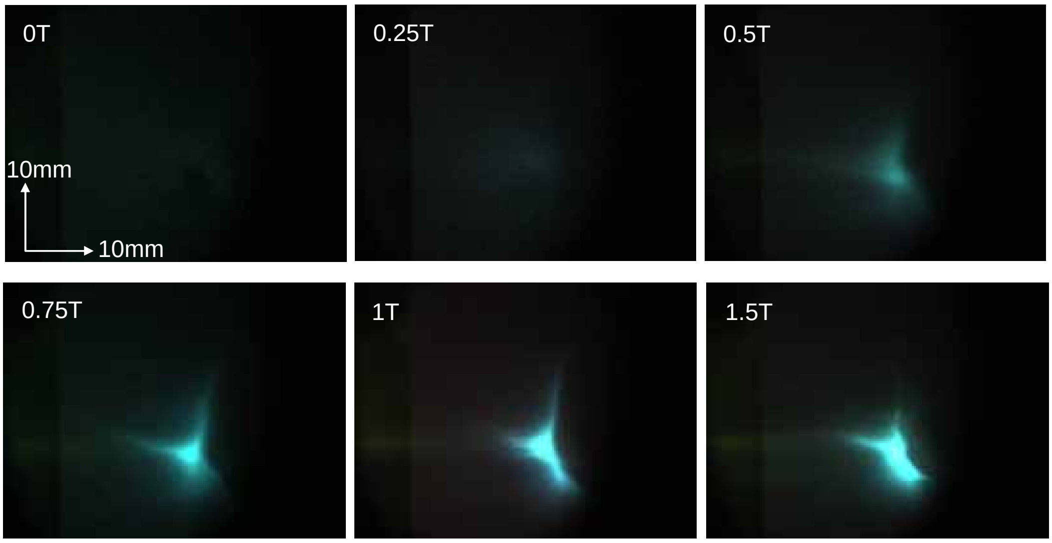

Fig.11 Measured beam shape

3. CONTINUOUS OPERATION

Long term continuous operation was tested with all component technologies to evaluate the effectiveness of the system. Tin droplet was 60 μm, CO_2 laser was kept as 5 kW at 2.4% duty, magnetic field was 0.6 T. Plasma flow along the magnetic filed line was observed as a continuous one, with no ion signals by off side Faraday cups. The operation was kept for 4 hours without any degradation of the components. The average conversion efficiency was 1.5%. Figure 12 shows the measured long term EUV output data.

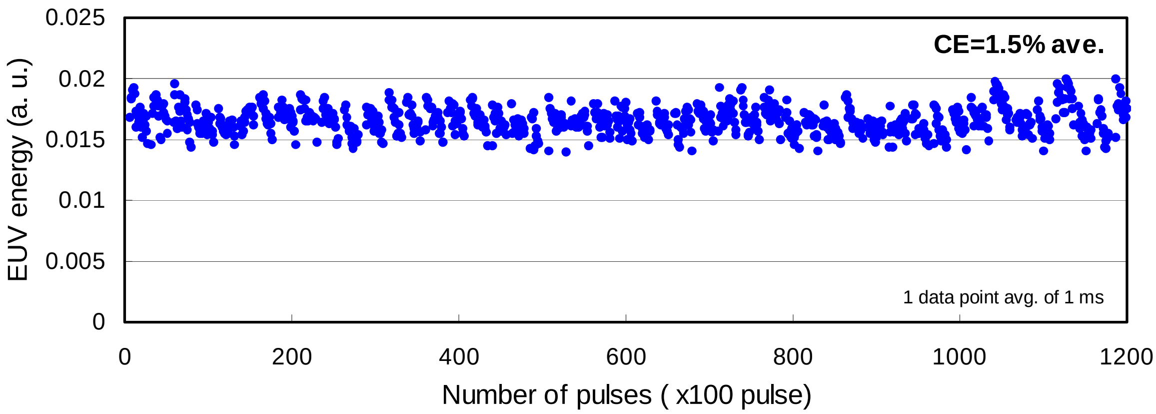

Fig. 12 Continuous operation

4. CONCLUSION

Steady progress was reported on the CO_2 laser produced Tin plasma method for HVM EUV light source. Pulsed CO_2 laser was operated at high duty continuously, without any degradation of the components with fine beam quality. Stability of the Tin droplet injector was improved for continuous operation in EUV plasma generation. Magnetic plasma guiding was well characterized on the dynamics. It was shown that a focusing of the stream plasma was stable to collect the injected Tin fuel into a Tin collector. Continuous operation has shown that the system is now matured for HVM EUV source.

ACKNOWLEDGEMENTS

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