CO_2 laser-produced Sn-plasma source for high-volume manufacturing EUV lithography

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ABSTRACT

We are developing a laser produced plasma light source for high volume manufacturing (HVM) EUV lithography. The light source is based on a high power, high repetition rate CO_2 laser system, a tin target and a magnetic ion guiding for tin treatment. The laser system is a master oscillator power amplifier (MOPA) configuration. We have achieved an average laser output power of 10 kW at 100 kHz by a single laser beam with good beam quality. EUV in-band power equivalent to 60 W at intermediate focus was produced by irradiating a tin rotating plate with 6 kW laser power. This light source is scalable to more than 200 W EUV in-band power based on a 20-kW CO_2 laser. Collector mirror life can be extended by using droplet target and magnetic ion guiding. Effectiveness of the magnetic ion guiding is examined by monitoring the motion of fast Sn ion in a large vacuum chamber with a maximum magnetic flux density of 2 T.

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

1. INTRODUCTION

A CO_2 laser produced tin (Sn) plasma light source is one of the most promising light source for extreme ultraviolet lithography (EUVL). A major technical challenge of an EUV light source for microlithography at 13.5 nm, is the in-band power requirement of more than 115W at the intermediate focus (IF)[1]. For a laser produced plasma (LPP) source, the best selection of the drive laser and the target material is therefore very important. Recent theoretical[2] and experimental[3] data clearly demonstrate the advantage of the combination of a CO_2 laser with a Sn target to achieve high conversion efficiency (CE) from laser pulse energy to EUV in-band energy. In addition, high average output power due to high amplification efficiency and superior beam quality is readily available from CO_2 lasers.

The important technical challenge using a Sn target is therefore tin treatment. A CO_2 laser creates much less debris compared with a Nd:YAG laser, as reported by us[4]. Fast ions, on the other hand, which are generated from the target surface during the ablation process and accelerated by ambipolar diffusion, can be controlled by a magnetic field[4,5], i.e. erosion of the collecting mirror multilayer or Sn ion attachment on the mirror surface is efficiently reduced.

Hence, our LPP EUV source system includes a CO_2 drive laser, a Sn droplet target supply system and a magnetic field for ion guiding as tin treatment. The CO_2 drive laser is based on industrial high average power CO_2 laser modules. The Sn droplet target is using continuous jet method. Control of a Sn droplet target chain is possible by charging and guiding by electromagnetic method[6]. Effectiveness of the magnetic ion guiding was examined by monitoring the fast Sn ion in a large vacuum chamber with a maximum magnetic flux density of 2 T. The characteristics of the system component and the EUV evaluation at IF point are described in this paper.

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2. CO_2 LASER PRODUCED SN PLASMA EUV SOURCE

2.1 CO_2 drive laser system

Carbon dioxide lasers are the most frequently used high power lasers for industry applications, because of robustness and reliability, as well as low initial and operational cost. RF-excitation is commonly employed scheme in axial flow or diffusion cooled slab or waveguide configurations, allowing high repetition rates at pulsed operation for laser plasma generation.

We have developed a short pulse CO_2 MOPA (Master Oscillator Power Amplifier) laser system with 20 ns pulse width and multi kW average power at 100 kHz repetition rate for plasma generation. Figure 1 shows the laser system configuration. The system consists of a short pulse high repetition rate oscillator and a multi stage amplifier. 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 with ZnSe windows.

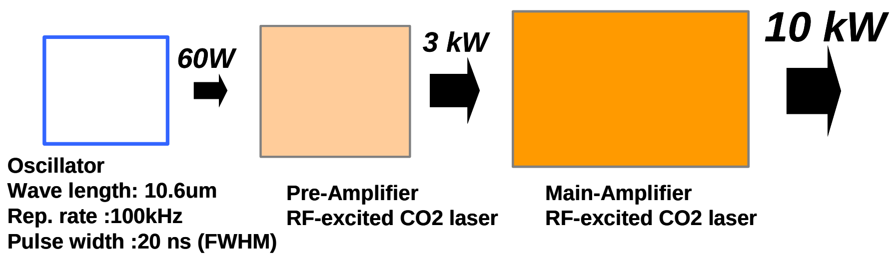


Fig.1. Configuration of the CO_2 MOPA system.

Efficient short pulse amplification with RF-pumped gain modules requires that parasitic oscillations and/or optical coupling between the amplifiers modules do not exist. We verified experimentally that no parasitic oscillations and/or optical coupling between the amplifier units exists: a power meter was placed behind the final amplifier stage and no signal was detected during maximum RF-pumping of all amplifiers. A pedestal and/or tail of the seed laser pulse can be also amplified and reduce the laser gain. Figure 2 shows the temporal laser pulse profile of amplified laser output. Pulse duration was 20 ns (FWHM) and the pedestal component was less than 10% of the total pulse energy.

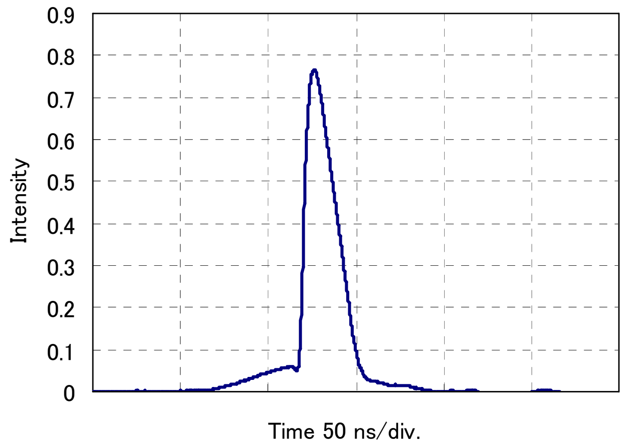


Fig. 2. Temporal laser pulse profile.

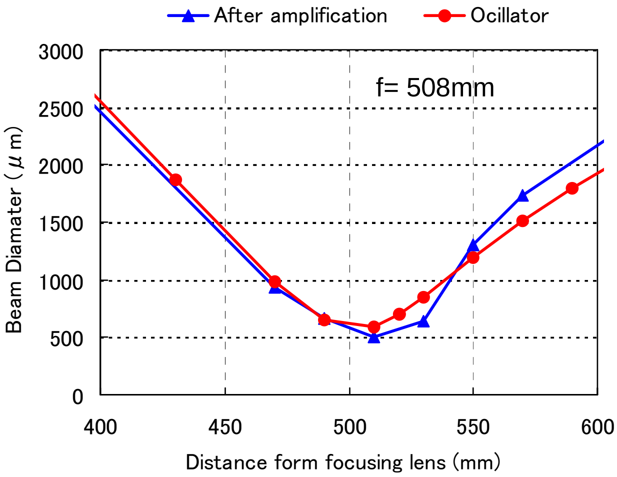


Fig. 3. Focus ability of the CO_2 laser beam.

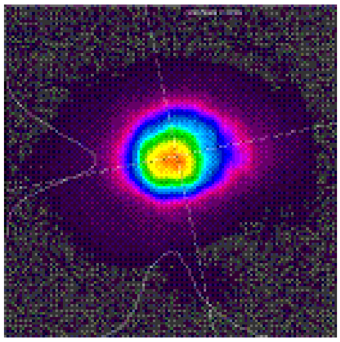


Fig4. Typical profile of the output laser beam.

The laser beam quality was measured with a ZnSe lens of 508 mm focal length and a slit-scan type beam profiler (Photon Inc., NanoScan). The laser beam size at the lens focus was measured for the oscillator and amplifier, see Fig.3, resulting in a beam propagation factor M^2 of 1.1. Especially, the laser beam size is identical before and after amplification, i.e. the amplification does not cause any phase distortion. Figure 4 shows a typical intensity profile of the amplified output laser beam.

The maximum average output laser power of 10 kW has been achieved at a repetition rate of 100 kHz from the MOPA system. The pulse laser amplification performance was evaluated by an extraction efficiency. The extraction efficiency E_{ex} is a ratio of amplified pulse laser power to a laser power at CW operation P_{cw} defined as,

$$E_{ex} = (P_{out} - P_{in}) / P_{cw} \qquad (1)$$

where P_{out} and P_{in} are output and input pulse laser power of an amplifier laser, respectively. The extraction efficiency of the main amplifier at 10 kW operation was over 30%. This was improved by increasing the overlap of laser gain medium and the laser beam in the amplifier modules.

2.2 EUV evaluation at IF

A system operation was done with the high power CO_2 MOPA laser, a solid rotating Sn disk target and a collector mirror to evaluate the EUV output performance at an IF point. The EUV pulse energy and EUV in-band image were measured. The EUV in-band image size is an important parameter as a lithography light source regarding to etendue limit requirement.

The laser beam from the CO_2 MOPA system was introduced to the EUV generation chamber. The laser output power was about 6 kW at the entrance window of the chamber. The laser beam was focused on to a solid rotating Sn disk that was preliminary used as a target supply. The laser incidence angle to the normal of the disk surface was 45 degree. The EUV radiation was collected to an IF point by an ellipsoidal collector mirror. The collector mirror was fan-shaped, third part of a π-sr (1 sr) solid angle, Mo/Si multilayer coated mirror. The average reflectivity of the mirror at 13.5 nm in-band EUV was more than 60%. A Zr foil was placed before the IF point as a spectral purity filter. EUV pulse energy and image at the IF point was measured by a calibrated photo diode (IRD) and an X-ray CCD camera, respectively.

The measured average EUV output energy and power collected by a 1-sr mirror at 100 kHz operation were 0.16 mJ and 16 W, respectively. The estimated EUV power is 60 W, if we use a 4-sr collector mirror that is technically available. Figure 5 shows the in-band EUV energy stability measured at the IF point at 100 kHz operation. The EUV output energy stability was 3.8% (3 sigma, 500 pulses). This energy stability will be improved by improving the irradiating laser pulse energy stability.

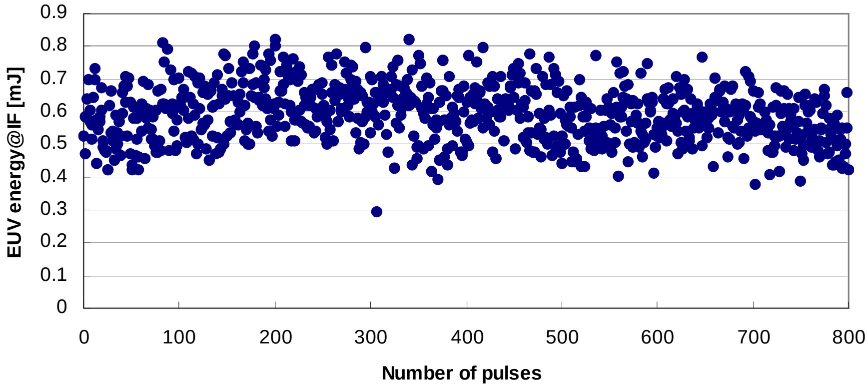


Fig. 5. EUV pulse energy stability at an IF point.

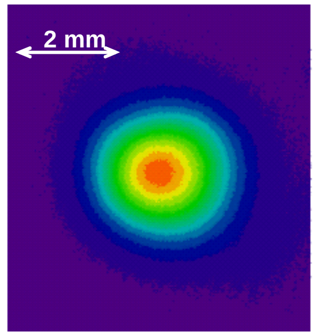


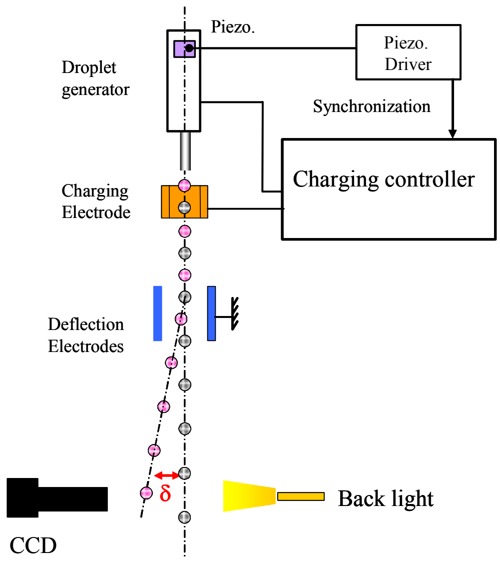
Fig. 6. EUV image at an IF point.

The measured EUV in-band image is shown in Fig. 6. A symmetric image profile was obtained. The horizontal and vertical image sizes were 3.6 mm and 3.3 mm, respectively, at $1/e^2$ of the peak intensity. The etendue of the source was 1.9 mm^2sr calculated from the source size at $1/e^2$ of the peak intensity and assuming a 4 sr collector mirror.

2.3 Sn droplet target supply

The Sn droplet target is an attractive target that can decrease the amount of debris by minimizing the drop size. Tin droplets with various diameters and spacing are generated by changing the nozzle inner diameter. We have generated minimum droplet diameter of about 20 µm at a frequency of 500 kHz with a velocity of about 20 m/s. Another attractive point of a droplet target is the controllability with an electromagnetic field by charging a droplet. Electrostatic charging is a widely used technology to charge droplet streams[7].

Figure 7 shows a schematic of a droplet generator and a droplet selection system via electrostatic charging. The Sn supply tank is heated above the melting point of Sn, 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 can be changed by adjusting the nozzle inner diameter and the PZT frequency.



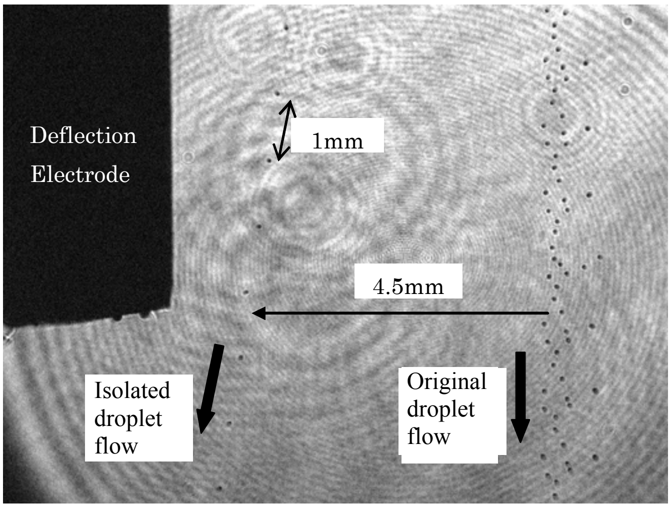


Fig. 7. Schematic of droplet generator and selection system.

Fig. 8. Isolated Sn droplets

Electrodes for droplet charging and deflection were placed below the nozzle. A liquid Sn jet first passes at breakup point the electrode area that selectively charges single droplets, which are then deflected, i.e. selected, by a second electrode pair.

We demonstrated droplet isolation with Sn droplets having a diameter of 40 μm. The original droplet train had a generation frequency of 177 kHz and a velocity of 17 m/s. The selection frequency was 17.7 kHz, i.e. the selection ratio was 1/10. Figure 8 shows isolated Sn droplets with uniform spacing of about 1mm. The deflection length is defined as the horizontal distance between the selected droplet and the initial droplet train. We obtained 4.5 mm deflection length at 60 mm from the nozzle with 2 kV charging electrode potential. The charge on a droplet calculated from the deflection length and the applied electrode potential was 1.1 pC.

We performed laser irradiation onto isolated Sn droplets. Droplets having 28 μm diameter and 70 μm spacing were generated at 300 kHz frequency. The selection frequency was 30 kHz. Hence one out of ten droplets was taken from the original droplet train and the selected droplets spacing was about 0.7mm. The deflection length at the laser irradiation point was more than 1mm. A Nd:YAG laser (1064 nm) having a spot size ($1/e^2$) of 300 μm and 10 mJ pulse energy was used. The Droplet behavior after laser irradiation was observed by a CCD camera with a illumination of synchronized flash lamp.

Figure 9 shows the droplet train 4 μs after a laser irradiation onto (a) continuous droplets and (b) isolated droplet. In case of the droplet train, several droplets within the laser spot area were hit and target material was sprayed into the laser propagation direction. In case of an isolated droplet, it is clearly seen that only one droplet was hit by the laser. In both cases the velocity of the tin spray is more than 150 – 200 m/s.

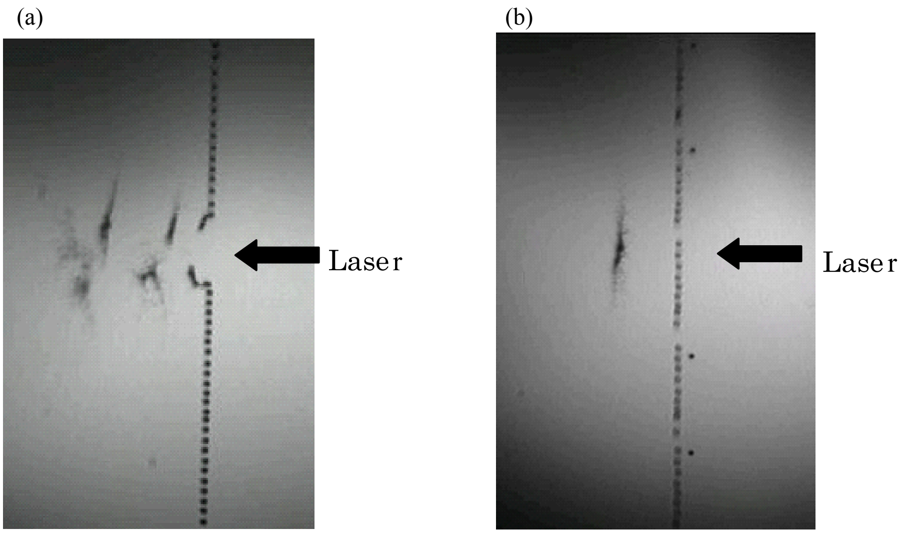


Fig. 9. Images taken 4μs after laser irradiation onto a) continuous droplets b) isolated droplet.

2.4 Magnetic field ion guiding as Sn treatment

The one of the most important technical challenge is the Sn treatment in an EUV plasma chamber to extend collector mirror lifetime. Tin deposition of only about 1 nm on an EUV collector mirror, i.e. only several atomic layers, reduces the mirror reflectivity by 10%, which is considered as the mirror lifetime specification. Therefore, Sn material has to be efficiently removed from the plasma region in order to prevent Sn from deposition (evaporated material, molten droplets, slow ions), erosion (fast ions), and implantation (ultra fast ions) on the collector mirror.

We previously reported Sn debris characteristics from Nd:YAG laser (1064 nm) and CO_2 laser (10.6 μm) driven plasmas using bulk Sn-plate targets and gold (Au) coated quartz crystal microbalances (QCM).[4,8] A CO_2 laser produced plasma generates less debris than a Nd:YAG laser driven plasma. The amount of neutrals from the CO_2 laser plasma was estimated to be 1% or less of the Nd:YAG laser plasma.

We have demonstrated the effectiveness of the magnetic field to prevent Sn ions from depositing on the collector mirror surface. Tin deposition on a Mo/Si sample mirror decreased by a factor of 4 by applying a magnetic field of 1 T[4,8]. But the vacuum chamber for this magnetic field experiment had a relatively narrow cylindrical volume of 5 cm in height and 50 cm in diameter. The Sn ion movement was therefore limited and a large magnetic field volume was a remaining issue.

We have installed a superconducting magnet to monitor the ion motion in a large vacuum chamber and to investigate effective Sn ion collection. This superconducting magnet has a vacuum chamber of 600-mm diameter placed inside the magnet bore. The maximum magnetic flux density at the plasma point is 2 T.

A preliminary experiment was conducted with a Sn plate target and a Nd:YAG laser. A Nd:YAG laser pulse of 100 mJ pulse energy and 8 ns duration irradiated a Sn plate target. The irradiated laser intensity was about 1.6 x 10^{11} W/cm^2.

Visible images taken by a CCD camera at different delay times from 1 to 8 μs are shown in Fig. 10. A Sn plate target was located at the left side of Fig. 10. A witness plate was placed at the right side in Fig. 10 and emitted blue light when fast ions hit its surface.

It can be seen that Sn ions are confined to the magnetic axis within about a 6 mm diameter region. The visible emission of the ion flow terminated within 10 μs, which corresponds to the plasma production interval at a repetition rate of 100 kHz. This preliminary experiment is a promising result for effective Sn collection.

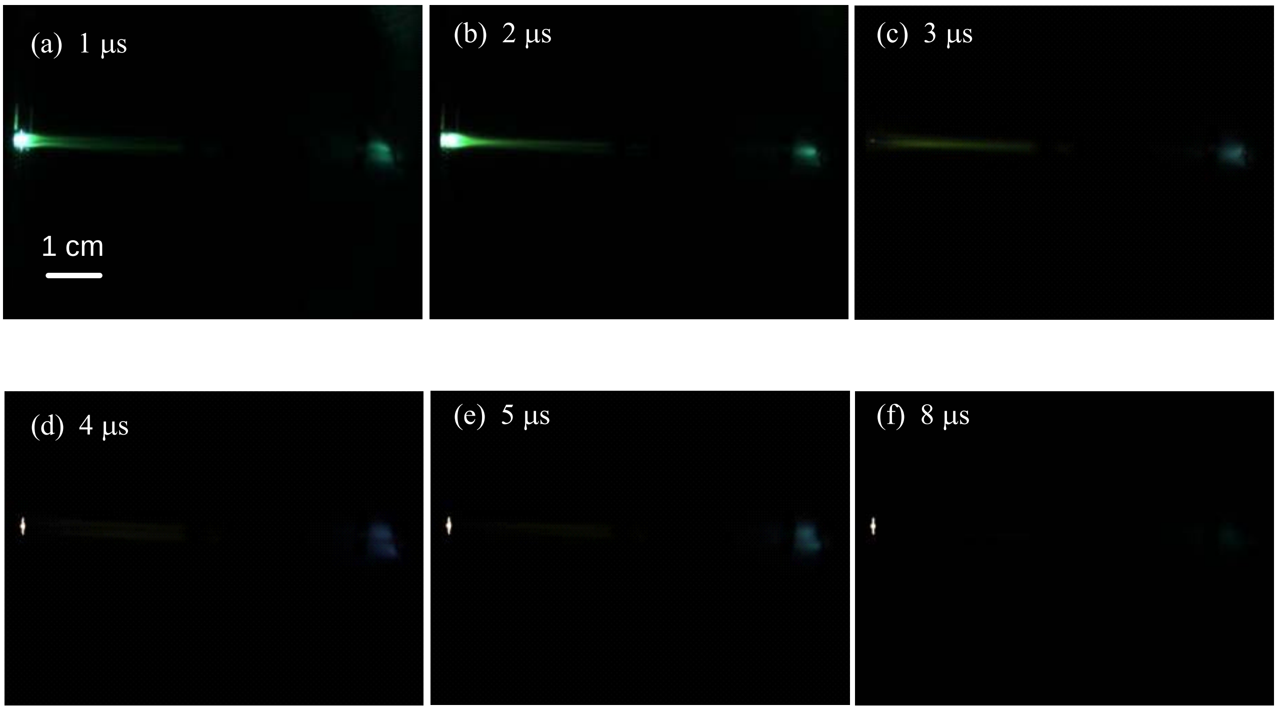


Fig. 10. Visible plasma image in a magnetic field of 2 T.

3. SUMMARY

We are developing a LPP source for high volume manufacturing EUV lithography that is based on a high power CO_2 MOPA system and a tin droplet target. A laser output power of 10 kW was achieved with a single beam having very good beam quality. The CO_2 laser based driver system allows for further power scaling. EUV in-band power equivalent to 60 W at intermediate focus was produced by irradiating a tin rotating plate with 6 kW laser power. This light source is scalable to more than 200 W EUV in-band power based on a 20-kW CO_2 laser. Effectiveness of the magnetic ion guiding as Sn treatment is examined by monitoring the fast Sn ion in a large magnetic field space. The ion flux from a Sn plasma was confined along the magnetic axis with a maximum magnetic flux density of 2 T. We conclude that the CO_2 laser driven Sn light source is the successful approach for HVM EUVL due to its power scalability, high efficiency and long collector mirror lifetime.

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