100W 1st Generation Laser-Produced Plasma light source system for HVM EUV lithography

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ABSTRACT

We reported 1st generation Laser-Produced Plasma source system "ETS" device for EUV lithography one year ago[1]. In this paper we update performance status of the 1st generation system. We have improved the system further, maximum burst power is 104W (100kHz, 1 mJ EUV power @ intermediate focus), laser-EUV conversion efficiency is 2.5%. Also continuous operation time is so far up to 8 hours with 5% duty cycle is achieved. We have investigated EUV plasma creation scheme by small experimental device which is facilitated 10Hz operation (maximum). We have proposed double pulse method to create LPP plasma efficiently. This moment we found out 3.3% conversion efficiency operation condition.

Based on the engineering data of ETS and small experimental device, now we are developing 2nd generation HVM source; GL200E. The device consists of the original concepts (1) CO_2 laser driven Sn plasma, (2) Hybrid CO_2 laser system that is combination of high speed (>100kHz) short pulse oscillator and industrial cw-CO_2, (3) Magnetic mitigation, and (4) Double pulse EUV plasma creation. The preliminary data are introduced in this paper.

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

1. INTRODUCTION

Since 2000 EUV light source is developed together with exposure tool. As α-tool with 10W EUV light source; ASML shipped "α-demo tool" in 2007[2] and Nikon shipped EUV-1 in 2008[3]. As β-tool ASML is now shipping NXE-3100 in the beginning of 2011 with 100W EUV light source[4]. The generation of EUV exposure tool requirement is now for γ tool. It is scheduled shipping in 2013. The required EUV power is 250 W clean power at intermediate focus on 2012.

Since 2002 we have developed CO_2 laser produced Tin plasma EUV source (CO_2-Sn-LPP) which is the most promising solution as the 13.5nm high power (> 200W) light source for high volume production extreme ultraviolet lithography (EUVL)[5]. Because of its high efficiency, scalability and spatial freedom from plasma, we believe the CO_2-Sn-LPP scheme is most promising candidate. Up to now, our group have proposed several unique original technologies such as (1) CO_2 laser driven Sn plasma, (2) Hybrid CO_2 laser system that is combination of high speed (>100kHz) short pulse oscillator and industrial cw-CO_2, (3) Magnetic mitigation, and (4) Double pulse EUV plasma creation. Theoretical[6] and experimental[7] 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.

One of the real technical challenges is the requirement of high average in-band power in other word high conversion efficiency, together with the cleanness of the plasma chamber. The other challenge is high average power, and superior beam quality CO_2 laser[8] which is based on industrial high average power cw CO_2 laser. It is essential. In this paper we report the present status of LPP light source for HVM source.

2. 1ST GENERATION SYSTEM EXPERIMENT [1]

The 1st generation integrated LPP system is shown in figure 1. Main configuration is shown in Table 1. We have demonstrated the technical concept of ; (1) Pre-pulse target conditioning, (2) Mass limited target and magnetic mitigation (3) Mirror cleaning technologies. We clarify the engineering issues of component and find solution for the multi 13kW high power CO_2 laser.

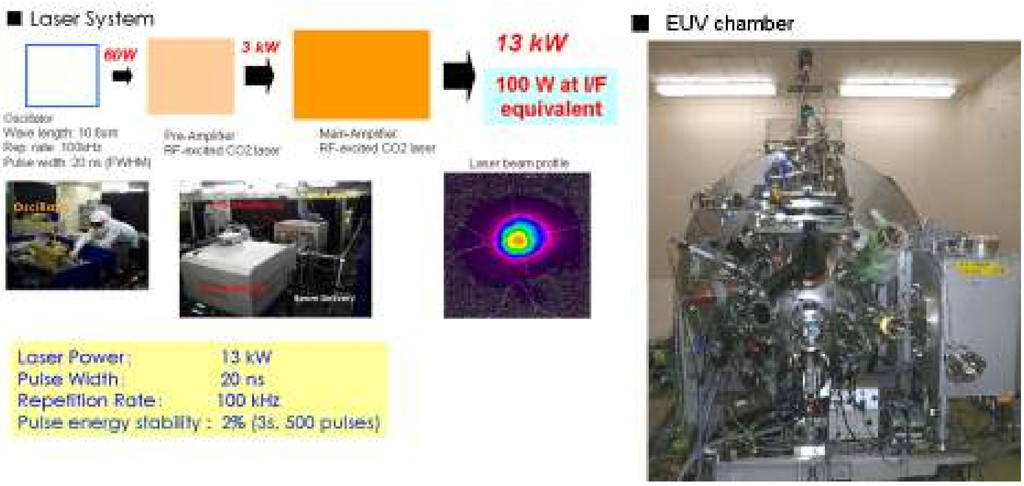


Fig.1 Outlook of ETS LPP-EUV source system

Table 1 Target specification of ETS device

EUV model	Engineering Test Stand device
EUV Power (@I/F)	104W (duty 20%)
EUV Power (@I/F clean)	50W
EUV Pulse energy (@I/F)	> 1 mJ
Max Rep. Rate	100 kHz
Max CO_2 laser system	13 kW (20ns, 100kHz, 100mJ)
Target material and shape	Sn droplet
Droplet size	60μm diameter → **30μm diameter**
Plasma creation	Pre-pulse conditioning + Main pulse heating
Debris mitigation	Magnetic field

The device demonstrated maximum power of 104W (50W clean power) and average power 21W (duty 20%) in system operation in April 2010[9]. Recently we have tried long-term operation. Main reason of the extension of the operation data is realized by smaller droplet size from 60μm to 30μm. The operation stability of droplet is shown in Figure 2. Especially, the fragment from the droplet dramatically decreased. We achieved 42W (20W clean power) max power, CE=2.5% during 7 hours operation with duty cycle 5% (Figure 3). The limit of operation (>7 hours) comes from thermal drift of base structure. The root cause of the issue is clarified from engineering data of several points temperature in the device. These data and experience are feed backed to the design of generation 2nd EUV device. In Table 2 the history of the data of ETS device is summarized.

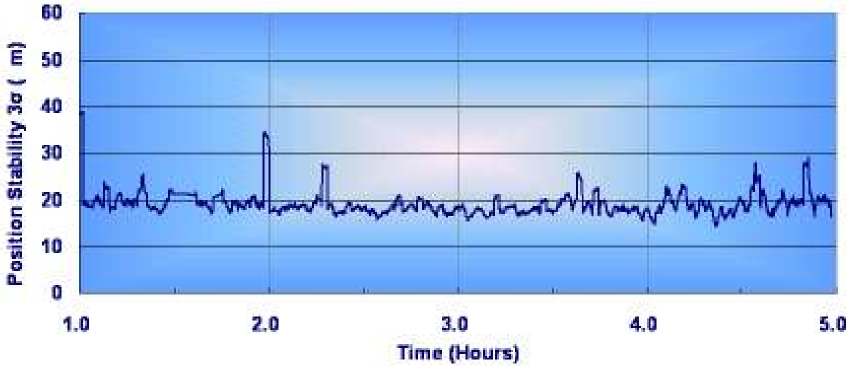


Figure 2 30μm droplet stability

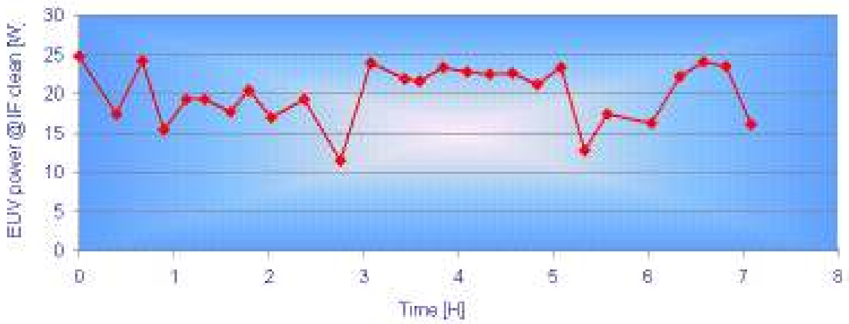


Figure 3 Opretion data of EUV power

Table 2 History of data at ETS device

	Data-1 (Feb.2010)[1]	Data-2 (Oct.2010)[9]	Data-3 (Feb.2011)
EUV power (@ I/F)	69 W	104 W	42 W
EUV power (clean @ I/F)	33 W	50 W	20 W
Duty cycle	20 %	20 %	5%
Max. non stop op. time	>1 hr	<1 hr	>7 hr
Average CE	2.3 %	2.5 %	2.1%
Dose stability :simulation	(+/- 0.15%)		-
Droplet diameter	60μm	60μm	30μm
CO_2 laser power	5.6 kW	7.9 kW	3.6kW

3. SMALL EXPERIMENTAL DEVICE[13]

We have investigated EUV plasma creation scheme by small experimental device which is facilitated 10Hz operation (maximum). Figure 4 shows the experimental setup for basic investigation of EUV light generation and Sn particles mitigation[10]. This system simulates the same conditions, for example pulse width and pulse energy of a CO_2 laser, tin droplet size and magnetic field, as the high-power EUV light source we develop except for the pulse repetition rate. Because of the compactness of the system it is easy to measure and optimize many irradiation parameters. The EUV system mainly consists of a short-pulsed high-energy CO_2 laser, a pre-pulse laser, a tin droplet generator and a EUV vacuum chamber with a solenoid magnet. The droplet generator can supply a droplet with a diameter of 10 μm at a minimum. The system operates at a frequency of 10Hz. The vacuum chamber is evacuated by a turbo molecular pump.

As previously described, Sn debris are generally classified into fragments, neutral atoms and ions. Sn fragments are measured by a shadowgraph method with a short-pulsed back illuminator and a CCD camera with a high-resolution telescope. Figure 5 shows a shadowgraph image of Sn droplet with a diameter of 20 μm. In order to investigate a behavior of Sn neutral atoms under a high-magnetic field, Sn atoms from laser plasma with a planar target are measured by LIF method. Sn atoms are excited by a 3rd harmonics of narrow-band Ti:sapphire laser which is tuned at the transition of $5p^2\ ^3P_0 - 6s\ ^3P^o_1$ (286.3 nm). The fluorescence from the transition of $5p^2\ ^3P_2 - 6s\ ^3P^o_1$ (317.5 nm) is observed with an image intensified CCD (ICCD) camera through a band-pass filter. The energy level diagram of Sn atom is shown in Figure 6. A Two-dimensional atom distributions are obtained with a thin line-profiled laser beam probed from a direction perpendicular to the Sn target surface.

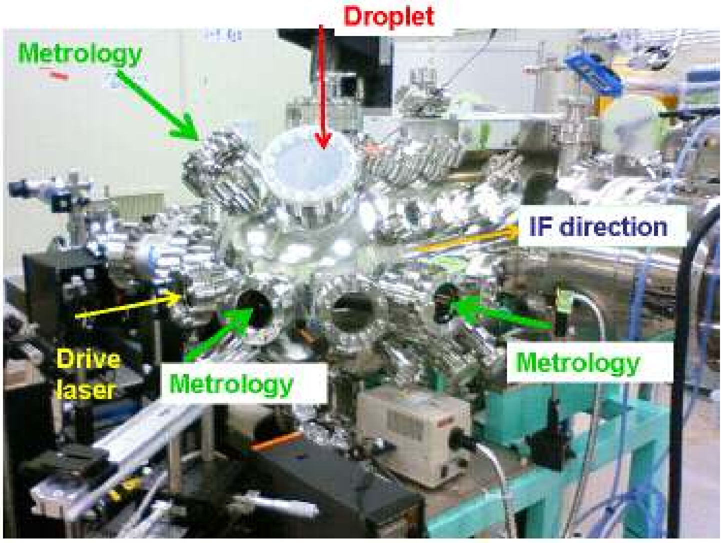


Figure 4 Picture of small experimental device

Sn fragments are generated after the pre-pulse irradiation. The Sn fragment is a majority of Sn debris. The diameter of the fragment reaches a few micrometers at a maximum. Figure 5 shows the shadowgraphs of the fragments after the pre-pulse laser irradiation for the droplet with 20 μm in diameter. The pre-pulse laser is irradiated onto the droplet from the left hand side of the image. After laser irradiation, the droplet is moved to the opposite side while expanding larger diameter. Figure 5a shows the images after the pre-pulse laser irradiation without the main CO_2 laser pulse irradiation. Figure 5b shows the images with the main CO_2 laser pulse. The center image is captured during the main pulse irradiation. The right-hand image is captured just after the EUV plasma emission. In this case, the fragments are vanished from the shadowgraph image. We believe almost all of the fragments are at least vaporized. Figure 5 is the ideal case optimized the laser irradiation conditions. On the other hand, figure 6 shows an example of a wrong laser irradiation condition. The right-hand shadowgraph image of figure 6b is obtained after the main laser pulse irradiation. Quite a few fragments still remain without vaporization. As a consequence of the experiment, it is found that fragments generated after the pre-pulse irradiation can be vaporized, then probably ionized, by reducing the droplet size below 20 μm and optimizing the laser irradiation parameters.

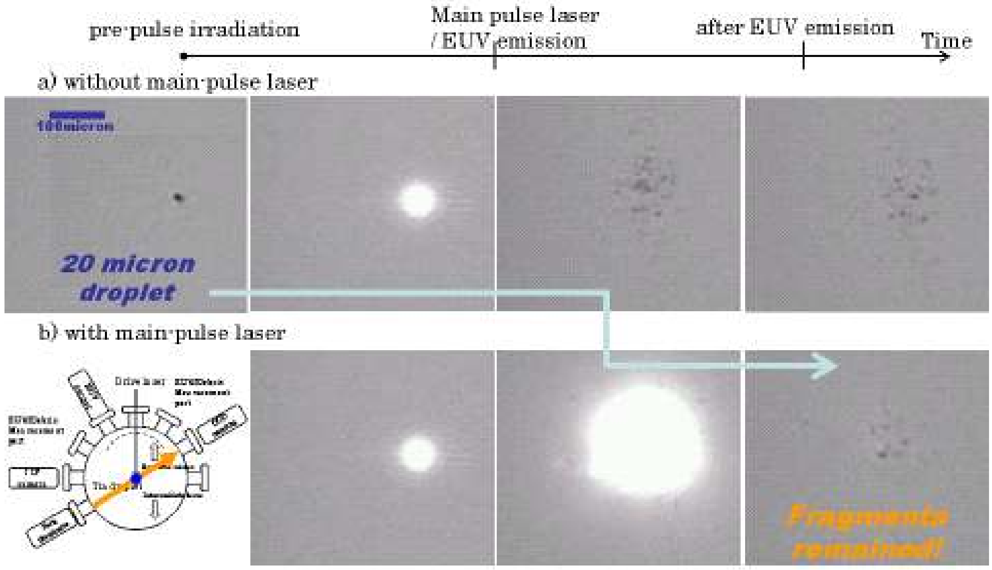


Figure 5. Shadowgraph images of the Sn fragments I (a proper condition)

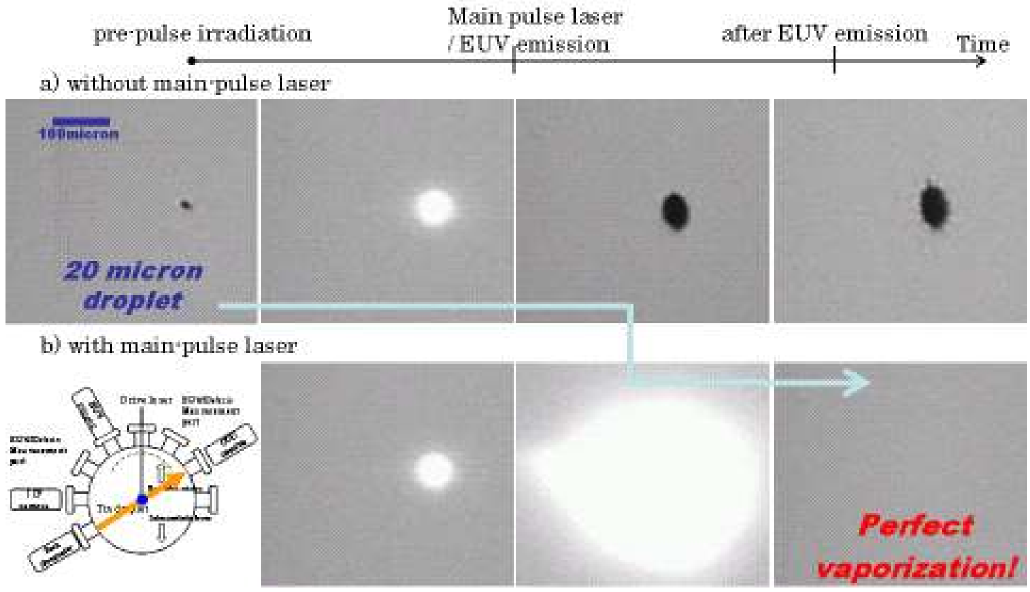


Figure 6. Shadowgraph images of the Sn fragments II (a wrong condition)

Figure 7 shows the EUV CE as a function of the droplet diameter. The pre-pulse is a key parameter for a higher EUV CE. The EUV CE reached to 3.3% for the 20 μm droplet by optimizing the pre-pulse laser conditions. Figure 7 depicts the EUV clean pulse energy for the 20 μm droplet as a function of the pulse energy of the CO_2 laser under the optimum pre-pulse condition. The equivalent clean EUV power which is calculated with the condition of our developing system with the pulse repletion rate of 100kHz also represents in figure 7. The maximum EUV clean power of 100 W is expected for the system condition.

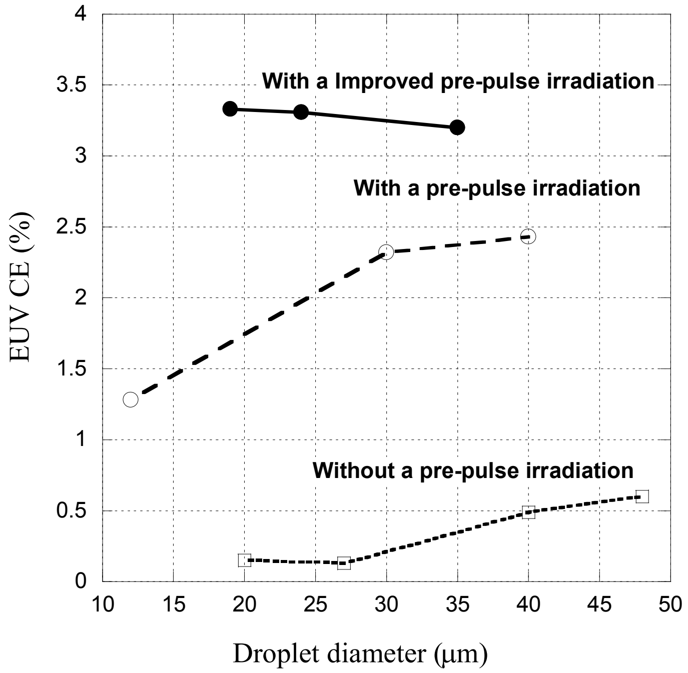


Figure 7. EUV CE as a function of the droplet diameter

The optimization of tin debris mitigation with the compact EUV generation system is presented. We confirmed that the Sn fragments generated from the 20 μm diameter droplet after the pre-pulse irradiation was vaporized almost entirely by adjusting the pre-pulse laser and main-pulse laser parameters. The Sn neutral atoms after the pre-pulse laser irradiation were observed with the LIF method. The Sn atoms from the planar target are converged and ejected along the magnetic field. This result proves the magnetic field is beneficial to the Sn particles guiding of not only the ions but also the neutral atoms. Finally the EUV CE with the droplet target is measured. The EUV-CE of 3.3% for the 20 μm diameter droplet is demonstrated by optimizing the pre-pulse laser conditions. We thus obtained the way of the debris reduction with the use of the 20 μm diameter droplet target without the degradation of the EUV CE. These basic studies contribute to the development of the high-power production machine and to the basic design for further EUV power scaling together with theoretical calculations.

4. 2ND GENERATION SYSTEM DEVELOPMENT

4-1 Light source system[12)]

We review the requirements of a CO_2 laser as an industrial LPP type EUV light source. Higher efficiency and operational reliability of the system are key for industrial use. Figure 8 shows the typical setup of the EUV light source system. The EUV chamber contains droplet generator, ion collector, C1 mirror, mirror stage, vacuum vessel and vacuum pump. Main function of the EUV chamber is to maintain the high level vacuum circumstance around EUV plasma, and mechanical position of components like, C1 mirror, droplet generator very stably. One of the most important requirements is fully capturing Tin from the EUV plasma chamber, to extend collector mirror lifetime. Tin deposition of even 1 nm layer on a EUV collector mirror, i.e. a few atomic layers, reduces the mirror reflectivity by 10%, which is considered to be 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.

To minimize optical loss of EUV, the EUV generation vessel is located closely beside the scanners. To minimize footprint in a clean room, the CO_2 laser system is located on a different floor (usually downstairs) from where the scanner is located. These two places have different vibration design specifications. Also 3-dimensional layout is shown in Figure 9.Usually, the floor where the CO_2 laser is installed is less stiff than where the scanner is located. Table 3 shows the major requirements of EUV light source system and the driver laser.

Table 3. Major target specifications of EUV and CO_2 Laser

	units	Specifications
EUV power (13.5 nm)	W	250
EUV power stability 3σ	%	12.0
Conversion Efficiency*	%	5.0
CO_2 power (10.6 μm)	kW	23
CO_2 laser pulse duration	nsec	15 – 20
CO_2 laser energy stability 3σ	%	6.0

*CE: conversion efficiency from CO_2 laser to EUV light

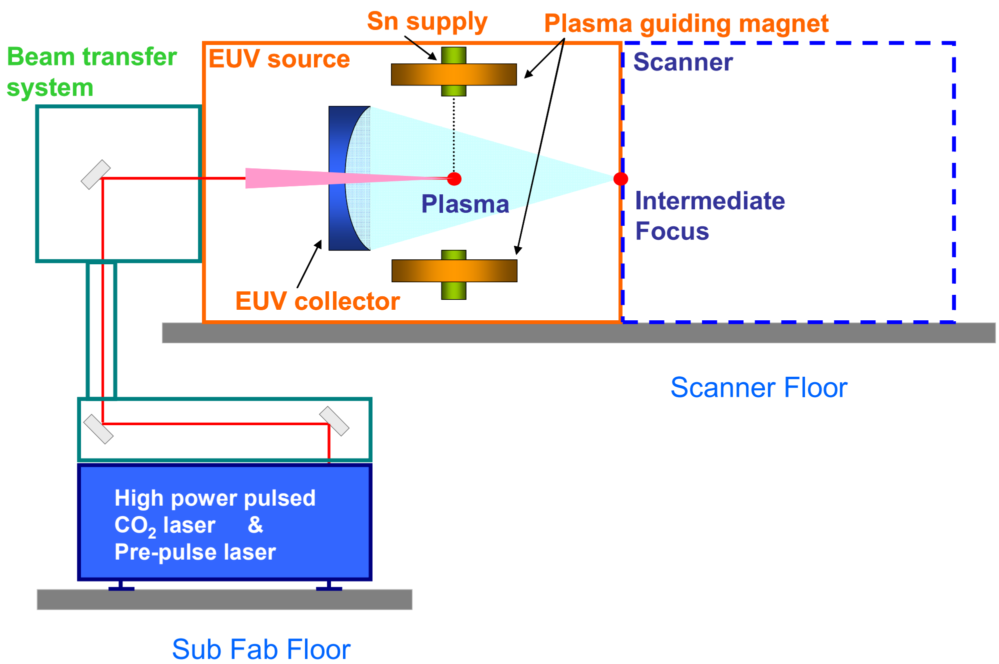


Figure 8. LPP EUV light source System

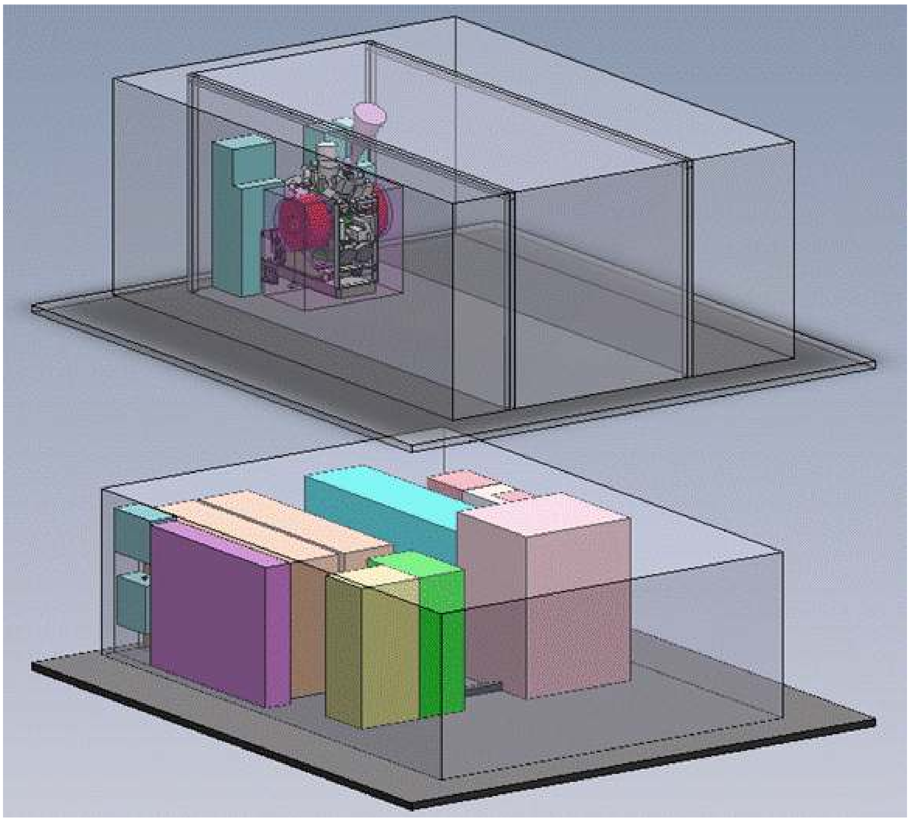


Figure 9 Layout of GL-200E LPP EUV system

4-2 Hybrid CO_2 laser system[12)]

Short pulse CO_2 MOPA (Master Oscillator Power Amplifier) laser system with 20 ns pulse width and 23kW average power at 100 kHz repetition rate. The hybrid system which 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. 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. Commercial industrial CW CO_2 lasers are used as amplifiers after some modification. The laser system is operable from low duty mode (2%) to full duty mode (100%).

The targeted specifications of this laser system are described below. The Oscillator (OSC) generates pulses at the repetition rate of 100 kHz, with 20 nsec pulse duration, and with 150 W (1.5 mJ, 100 kHz) power. The OSC contains two major parts. One is master-OSC that oscillates a pulse, and the other is OSC-AMP that amplifies the pulse energy. The pre-amplifier (pre-AMP) amplifies the pulse from 150 W to 3 kW (30 mJ, 100 kHz) output level with the slab-type discharge chamber. The main-amplifiers (main-AMP) further amplify the pulse from 3 kW to 23 kW (230 mJ, 100 kHz) output level with the two sets of fast gasflow-tube-type discharge systems. This system has has laser beam path that is approximately 100 m long. The laser goes out of alignment mainly due to the vibration propagated from the floor and the thermal deformation of optics caused as the laser power is absorbed in and on the mirrors, which causes the beam direction to fluctuate. The main-AMP amplifies the pulse from 1.7 kW (17 mJ, 100 kHz) to 7.6 kW (76 mJ 100 kHz, target 20 kW) and inputs the pulse to the EUV vessel. The results are shown in Figure 10. The performance of the input and output characteristics at RF duty of 80% at 200 kW, output power at input of 1.7 kW, the beam profile, and the pulse duration are also shown.

Each module shows the performance at feasible level to meet the system specifications. The master-OSC, the OSC-AMP, the pre-AMP, and the main-AMP are going to be tuned for meeting the targeted specifications. The temporal laser pulse profile of the amplified output is shown. The pulse duration is 20 ns (FWHM) and the pedestal component was confirmed as less than 10% of the total output power. There is beam distortion in the active gas medium during amplification, but the thermal deformation of the solid optical components inside the beam delivery system, seems to be the main source of the beam quality degradation. Enough cooling and careful optimization of the material reduces these effects.

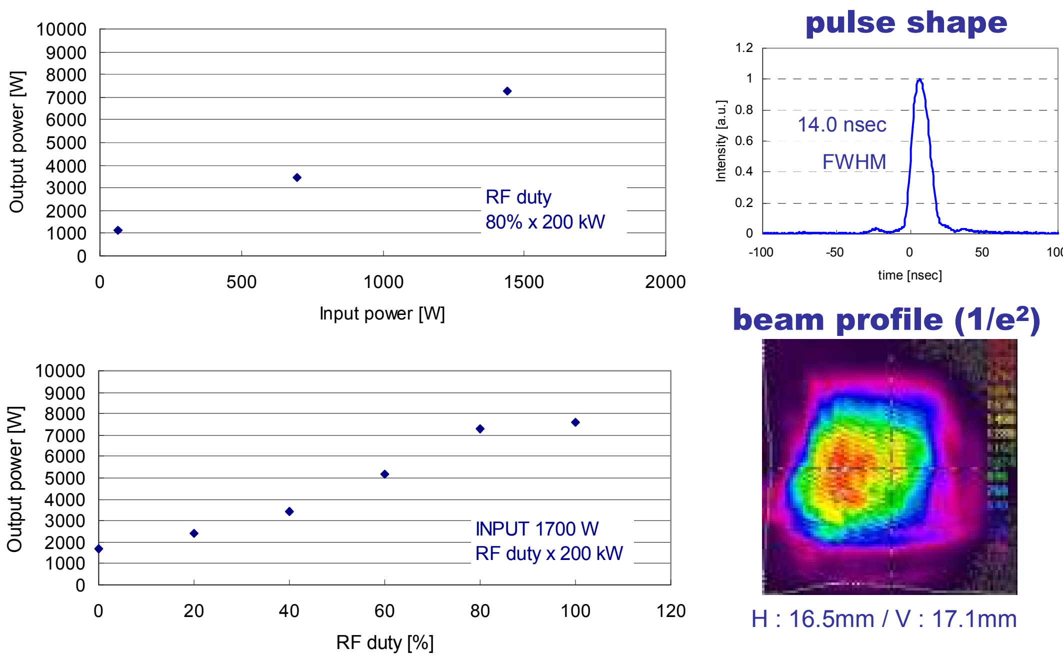
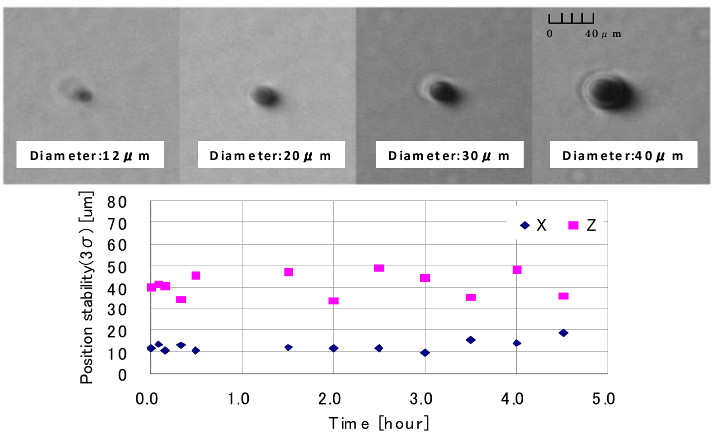


Figure 10 Beam profile of CO_2 laser

4-3 Droplet generator

As we explain at chapter 3, small tin droplet generation is essentially important to tin mitigation. The tin supply tank is heated above the melting temperature of Tin. The liquid Sn droplet is generated from the droplet generator. Generated droplet diameter is 12 μm - 40 μm. Stability of the 20 μm droplet at 6 kHz is reported in Figure 11. Long term stability of the droplet is another factor to guarantee the long term EUV IF power stability, the Z direction stability is still important issue for stabilization.



Position stability of 20 μ m @ 6 kHz w/o control, 1 point: 30 sec

Figure 11 Picture of droplet and 20 μ m droplet stability during 5hours

4-4 Latest status of GL200E construction

Based on the engineering data of ETS and small experimental device, now we are developing 2nd generation HVM source; GL200E. Figure 12 shows the construction of GL-200E EUV source system. Laser system is assembled in one clean room. Next step after the construction is demonstration of power and short-, long- term stability and debris free operation with 100W level output.

Our challenges to 250W level will be realized by extension of CO_2 laser power from 13kW to 23kW and conversion efficiency from 3% to 5%. Figure 13 shows our target performance and status at present.

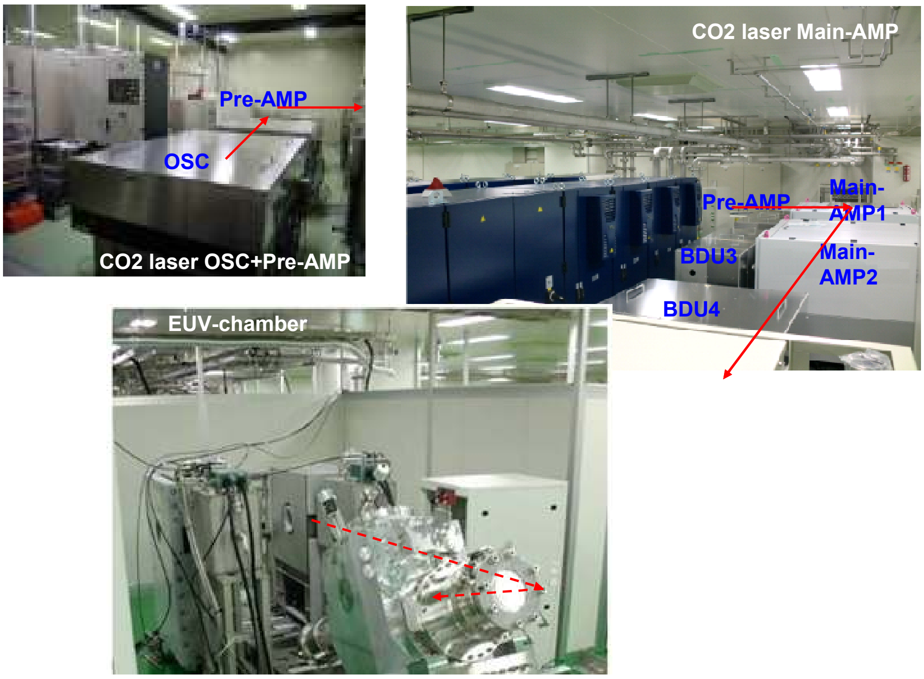


Figure 12 Picture of GL-200E proto system

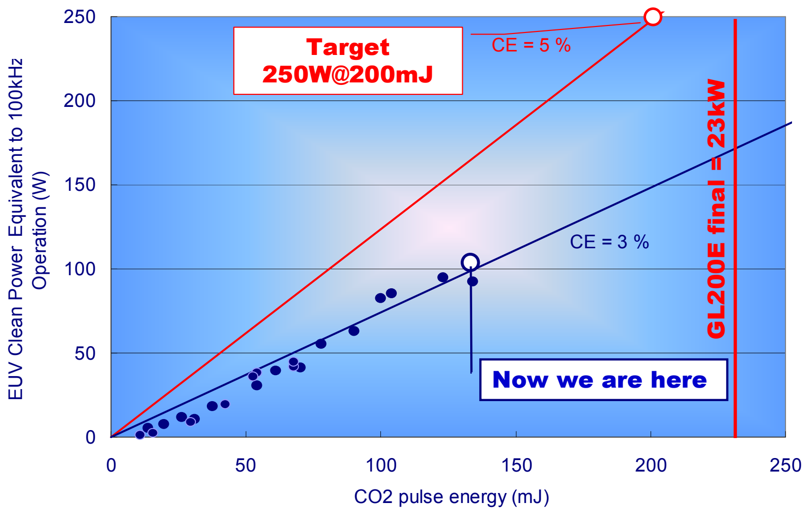
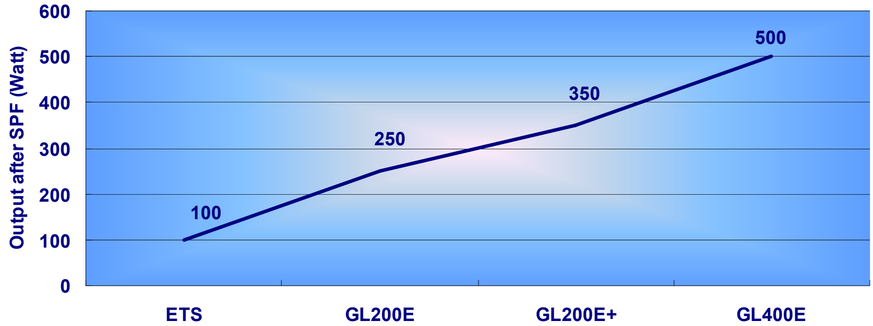


Figure 13 Scalability of CO2 energy and EUV power

5. FUTURE PLAN

The road map of Gigaphoton LPP EUV source is shown in Figure 14. After ETS device we have a plan to develop 2nd generation 250W GL200E in 2011. After that we develop 350W device as GL200E+ with upgrade of GL200E configuration. In 2014 we will release 500W device named GL400E. Our plan is strongly support the requirement of lithography tool advance[11)].



EUV model		ETS	GL200E	GL200E+	GL400E
Drive laser power	kW	10	23	33	40
Conversion efficiency	%	3.0	5.0	5.0	6.0
C1 mirror collector angle	sr	5.5	5.5	5.5	5.5
efficiency*	%	74	74	74	74
C1 mirror reflectivity	%	(50)	57	57	57
Optical transmission	%	95	95	95	95
SPF (IR, DUV)	%	N/A**	62	62	62
Total EUV power (after SF	W	100	250	350	500

Figure 14 Road map of Gigaphoton LPP EUV source

6. CONCLUSION

We reported 1st generation Laser-Produced Plasma source system "ETS" device for EUV lithography one year ago[1)]. In this paper we update performance status of the 1st generation system. We have improved the system further, maximum burst power is 104W (100kHz, 1 mJ EUV power @ intermediate focus), laser-EUV conversion efficiency is 2.5%. Also continuous operation time is so far up to 8 hours with 5% duty cycle is achieved. ETS experiment clarify 3 key engineering items are essential.(1)CE (Conversion Efficiency) improvement, (2)Debris mitigation = Stability and size of droplets (3)CO_2 laser load.

We have investigated EUV plasma creation scheme by small experimental device which is facilitated 10Hz operation (maximum). We have proposed double pulse method to create LPP plasma efficiently. This moment we found out 3.3% conversion efficiency operation condition.

Based on the engineering data of ETS and small experimental device, now we are developing 2nd generation HVM source; GL200E. The device consists of the original concepts (1) CO_2 laser driven Sn plasma, (2) Hybrid CO_2 laser system that is combination of high speed (>100kHz) short pulse oscillator and industrial cw-CO_2, (3) Magnetic mitigation, and (4) Double pulse EUV plasma creation. The preliminary data are introduced in this paper. Concept of design and outline is reported. We already finished final assembling and we are just preparing operation of first light.

7. ACKNOWLEDGEMENT

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