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Abstract

Since 2002, we have been developing a CO_2-Sn-LPP EUV light source, the most promising solution as the 13.5 nm high power (>200 W) light source for HVM EUV lithography. Because of its high efficiency, power scalability and spatial freedom around plasma, we believe that the CO_2-Sn-LPP scheme is the most feasible candidate as the light source for EUVL. By now, our group has proposed several unique original technologies such as CO_2 laser driven Sn plasma generation, double laser pulse shooting for higher Sn ionization rate and higher CE, Sn debris mitigation with a magnetic field, and a hybrid CO_2 laser system that is a combination of a short pulse oscillator and commercial cw-CO_2 amplifiers. The theoretical and experimental data have clearly demonstrated the advantage of combining a laser beam at a wavelength of the CO_2 laser system with Sn plasma to achieve high CE from driver laser pulse energy to EUV in-band energy. Combination of CO2 laser power and droplet generator improvements on new EUV chamber (Proto-2) enables stable EUV emission. EUV burst operation data shows stable average 10.2W(clean power @ I/F) EUV emission and maximum 20.3W(clean power @ I/F) was demonstrated.For future HVM the maximum of 4.7% CE with a 20 μm droplet are demonstrated by ps pre-pulse LPP. Also reported 40kW CO2 laser development project cooperate with Mitsubishi electric.

1. Introduction

Extreme ultraviolet (EUV) light source has been being developed together with a scanning exposure tool. As the α-tool with 10 W EUV light source, ASML shipped "α-demo tool" in 2007(1) and Nikon shipped EUV-1 in 2008.(2) The β-tool of ASML was NXE-3100 in the beginning of 2011 with 100 W EUV light source.(3)(4) The requirement of the EUV exposure tool development is now in the γ-tool (for high volume manufacturing (HVM)) stage. It is scheduled to be shipped in 2013. The required EUV power is 250 W clean power (after purifying infrared (IR) and deep ultra violet (DUV) spectra) at intermediate focus (IF). Since 2002, we have been developing the carbon dioxide (CO_2) laser produced Tin (Sn) plasma (CO_2-Sn-LPP) EUV light source which is the most promising solution as the 13.5 nm high power (>200 W) light source for HVM EUV lithography (EUVL).(5)(6)(7) We have chosen the LPP-EUV method because of its high efficiency, power scalability, and spatial freedom around plasma. Our group has proposed several unique original technologies:

(1) High efficient Sn plasma generation; driven by CO_2 laser

(2) Double pulse irradiation scheme for Sn plasma generation

(3) Sn debris mitigation by a magnetic field, a small droplet size (20 μm)

(4) Hybrid CO_2 laser system ; combination of a short pulse oscillator and commercial cw-CO_2 amplifiers

The theoretical(8) and experimental(9) data have clearly demonstrated the advantage of combining a laser beam at a wavelength of a CO_2 laser with Sn plasma to achieve high conversion efficiency (CE) from driver laser pulse energy to EUV in-band energy. One of the real technical challenges is the requirement for high average in-band energy. The other challenges include the requirements for high average power, and superior beam

Extreme Ultraviolet (EUV) Lithography IV, edited by Patrick P. Naulleau, Proc. of SPIE Vol. 8679, 86790A
© 2013 SPIE · CCC code: 0277-786X/13/$18 · doi: 10.1117/12.2014139

quality of CO_2 laser$^{10)}$ which is based on commercial high average power cw-CO_2 amplifiers. In this paper we report the present development status of the LPP light source for HVM.

2. LPP EUV light source system status

We have been developing LPP-EUV light source with two experimental systems: 1) the engineering test stand (ETS); and 2) the small experimental tool. The features of these systems are shown below. We are now developing GL200E system (see 3) below), which is going to be our first generation HVM EUV light source.

1) ETS device (Fig. 2)

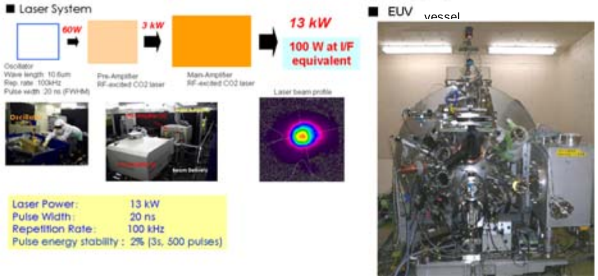

Fig.2 ETS device

Table 1 Experimental data of ETS device

	Data-1 (Feb.2010) [5]	Data-2 (Oct.2010) [11]	Data-3 (Feb.2011) [7]
EUV power (net @ 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 hour	<1 hour	>7 hour
average CE	2.3%	2.5%	2.1%
dose stability (simulated)	(+/- 0.15%)		-
droplet diameter	60 μm	60 μm	30 μm
CO_2 laser power	5.6 kW	7.9 kW	3.6 kW

The integrated experimental system for the total EUV light generation having kW level CO_2 laser, 30 - 60 μm in diameter droplet generator, magnetic field for debris mitigation. Our first integrated LPP-EUV light source system, which we call ETS, is shown in Fig. 2. This ETS has a vacuum chamber, 30 μm to 60 μm droplet generator, 100 kHz, 13 kW CO_2 laser, and superconductive magnet. The ETS has demonstrated maximum power of 50 W (clean power in burst) and average power of 10.1 W (clean power, duty 20%) at system operation in April 2010.$^{11)}$ In the experiment, the operation time was limited by the stability of droplet. The amount of fragments from the droplet dramatically decreased by the use of smaller droplet size. We have achieved 25 W (clean power) in maximum power, 2.5 % of CE during 7 hours of operating time with the duty cycle of 5 %. The operation time more than 7 hours was limited by the thermal drift in the base structure. Table 1 summarized the key parameters of the EUV source operation experiments.

(2) GL200E proto system (Fig. 3)

Prototype system of the first HVM EUV light source having 100 kHz 20 kW CO_2 laser, 20 μm in diameter droplet generator, magnetic field debris mitigation. The details of the above will be discussed in the following sections. The LPP-EUV light source system is configured of four primary parts. These are;

1) EUV vessel including a droplet generator and a collector mirror

2) Superconductive magnet for debris mitigation

3) Plasma generation driver lasers: pulsed CO_2 laser and pre-pulse laser

4) CO_2 laser power supply system

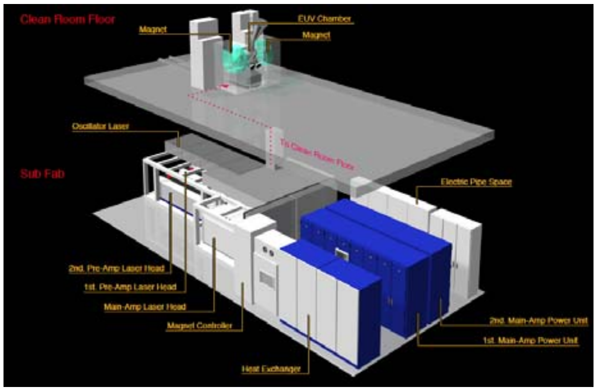

Fig.3 GL-200E HVM EUV source device

Model #	GL200E
EUV Power (@I/F clean)	250 W in-band; after filtering IR & DUV
EUV Pulse energy (@I/F)	- 2.5 mJ
Max. Rep. Rate	- 100 kHz
Max. CO_2 laser system	20 kW (20 ns, 100 kHz, 200 mJ)
Target material and shape	Liquid Sn droplet
Droplet size	- 30 μm diameter
Plasma creation scheme	Double pulse laser shooting
Debris mitigation	Hybrid; magnetic field guide & chemical etching

Table 2 Target Specification of GL-200E

The major specifications of the first generation HVM EUV light source are shown in Table 2. The EUV vessel contains, as primary components, a droplet generator, a collector mirror, and several vacuum pumps. In order to mitigate Sn debris, a pair of superconductive magnetic coils is arranged beside the vessel. The main function of the EUV vessel is to maintain high level vacuum environment around EUV plasma and to mechanically position the components, such as the collector mirror and the droplet generator and so on. One of the most important requirements is to fully capture Sn atoms after EUV radiation for the extension of the lifetime of the collector mirror. Sn deposition of even 1 nm thick layer on the EUV collector mirror, i.e. a few atomic layers, degrades the mirror reflectivity by 10 %, which needs to be taken into consideration in the mirror lifetime specification.12) The supplied Sn has to be almost 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 should be located closely beside the scanners. The clean room floor for the exposure tool is mainly occupied by the scanner. To minimize overall footprint in the clean room area, the CO_2 laser system should be located on a different floor (usually downstairs) from where the scanner is located.

3. KEY technology development

We have investigated EUV plasma generation scheme by our small experimental tool which is operated at the repetition rate of 10 Hz (maximum). Small experimental device simulate final system, except for the repetition rate of the driver laser, with/without magnetic field. It can simulate 20 kW CO_2 laser irradiation with pulse energy of 200 mJ/pulse and low repetition rate: less than 10 Hz. It has various measurement windows which can observe Sn behavior inside of vessel. As we have described, there are many key technologies that need to be developed to realize the LPP-EUV light source. In this section, the four major items are shown below. This tool is capable of simulating conditions of EUV light generation identical to those in ETS and GL200E, such as pulse duration and pulse energy of CO_2 laser and pre-pulse laser, Sn droplet size, and magnetic field environment except for the repetition rate[13)14)]. The tool's compactness makes it easier to measure and optimize various plasma generation parameters and results. The small experimental tool consists of various sub systems, such as a short-pulsed high-energy CO_2 laser, a pre-pulse laser, a Sn droplet generator, and a EUV vacuum vessel with a solenoid magnet. The droplet generator can supply a droplet with a diameter of around 20 µm. The system operates at a repetition rate of 10 Hz at maximum. The vacuum vessel is evacuated by a turbo molecular pump and a dry pump. By using this tool, we investigate EUV light emission under a pre-pulse laser and a CO_2 laser irradiation.

3.1 Droplet generator and control system

The small Sn droplet generation is particularly important in Sn debris mitigation. The mass of Sn should be minimized to what is necessary to obtain EUV photons. The Sn supply tank is heated above the melting temperature of Sn (>231.93 degree Celsius). The liquid Sn droplets are generated from the droplet generator. The generated droplet is around 12 µm - 40 µm in diameter. The schematic of droplet generator is shown in Fig. 5. Small droplet created at the nozzle is pulled by electrical field and accelerated and diffracted by each electrodes(accelerator and deflector). The Tin droplet is operate by on demand electrical voltage control; we call this type as "on demand type droplet generator". The long term positional stability of the droplets is indispensable to maintain the long term EUV IF power stability. The droplet position is measured by a position sensor and the results are fed back to the droplet generator stage. This is very important because the droplet position determines the EUV light source position. Also pre-pulse laser and CO_2 laser irradiation positions are monitored, which, combined with monitoring of the droplet position, enables to stabilize CE and EUV light source position and to improve Sn debris mitigation, and is extremely important for commercial use. The EUV light source system is equipped with droplet position sensors and controllers; it also has pre-pulse laser and CO_2 laser position controllers to stabilize plasma position and the EUV energy.

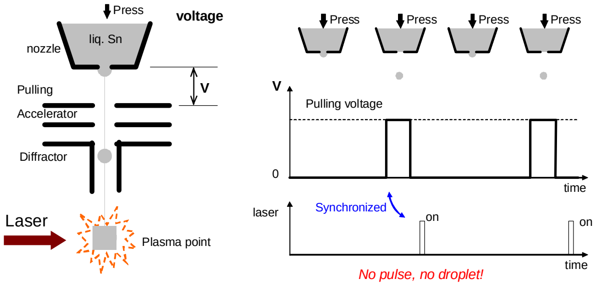

Fig.5 Droplet generator (on demand type)

3.2 Pre-pulse technology

When a Sn droplet target is irradiated with pre-pulse laser and/or CO_2 laser beams, the Sn droplet is spread over in the vessel as plasma and several states of Sn. The Sn is classified generally into fragments, neutral atoms, and ions. During spreading process Sn plasma emits EUV light. Residues of the plasma after emitting EUV light are eventually scattered inside the vessel. To prevent the collector mirror from being contaminated, Sn debris needs to be trapped before being deposited on the collector mirror. To enhance EUV energy and to maximize Sn debris mitigation, Sn ions should be maximized in these laser irradiation processes. We believe that the shape of Sn target is crucial. To realize it, the double laser irradiation process is utilized in our system.

Firstly we found that the Sn fragments are generated after the pre-pulse irradiation. The Sn fragments are the major parts of the Sn. The diameter of the fragments reaches a few micrometers at the maximum. The Sn fragments are measured by a shadowgraph method with a few nanosecond pulsed back illuminator and a CCD camera with a high-resolution telescope. Fig. 6 show the shadowgraphs of the fragments after the pre-pulse laser irradiation for the droplet with 20 μm diameter. The droplet is irradiated with the pre-pulse laser from left hand side in the image. After the laser irradiation, the droplet is moved to the opposite side while expanding in diameter. The images after the pre-pulse laser irradiation without the main CO_2 laser irradiation (upper) and the images with the main CO_2 laser irradiation(bottom). The middle images are captured during the main pulse irradiation. The image on the right-hand side is captured immediately after the EUV light emission. In this case, the fragments have disappeared from the shadowgraph image. We believe that almost all of the fragments have been vaporized. This Fig.6 is the ideal case of optimized laser irradiation conditions.

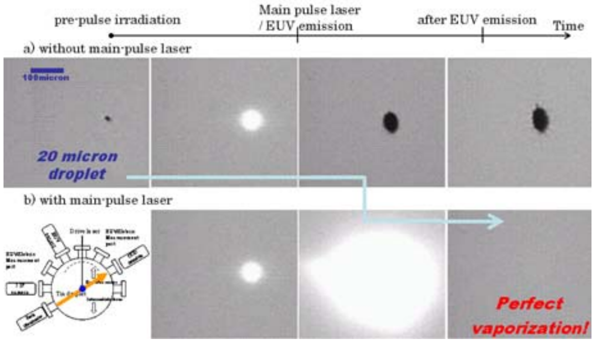

Fig.6 Double pulse plasma creation (1) – optimum

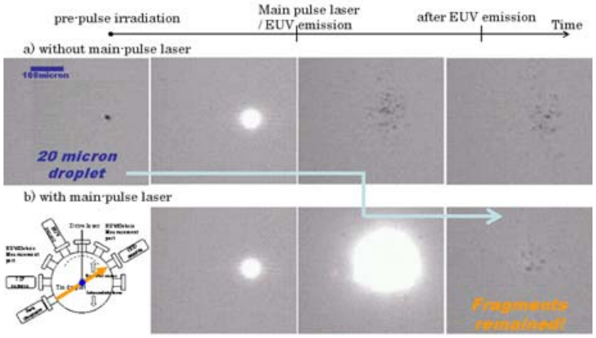

Fig.7 Double pulse plasma creation (2) – non-optimum

On the other hand, Fig.7 shows an example of an non-optimum laser irradiation condition. The shadowgraph image on the right-hand side in Fig. 7 is obtained after the main pulse laser irradiation. Some fragments still remain without being vaporized. From the results of the experiment, we found that the fragments generated after the pre-pulse irradiation could be vaporized with appropriate laser irradiation condition, and could be ionized partially. The Sn ionization rate will be discussed in the following section. Also it can be optimizing the laser irradiation parameters such as by reducing the droplet size to below 20 μm in diameter. We have investigated the CE as a function of the droplet diameter with/without pre-pulse laser conditions. Fig.8 shows the results, which indicate that high CE can be obtained even with the small droplet size. The pre-pulse laser condition is a key parameter for obtaining higher CE. The CE reached 3.3 % with the 20 μm droplet by optimizing the pre-pulse laser conditions. Fig.9 shows 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 laser condition. The maximum value is observed for the CO_2 pulse energy of 134 mJ at the maximum. It is clear that the CE has not saturated in the CO_2 pulse energy range.

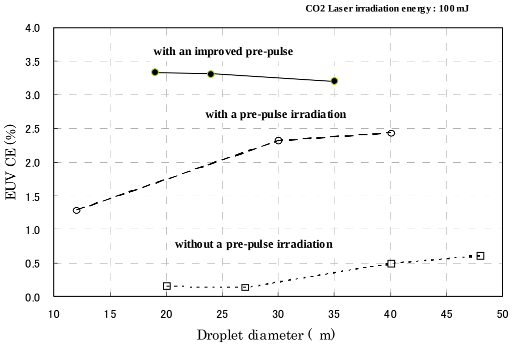

Fig.8 CE vs. droplet diameter

3.3 Sn debris magnetic mitigation technology

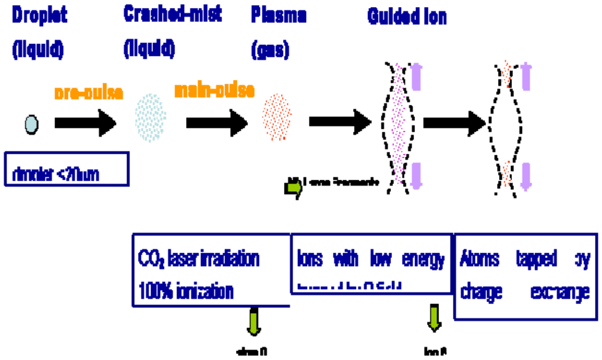

Fig.11 Debris mitigation schematic

Our Sn debris mitigation concept with the magnetic field is simple. Because EUV light is emitted from the Sn plasma, which is mainly composed of Sn ions, almost all the Sn ions can be trapped in the magnetic field. Further, when the Sn ions are maximized, higher CE can be obtained. We have shown the Sn fragments distribution shape in section 3-2. It is the essential to obtain higher CE. The CO_2 laser absorption could be changed with this fragments condition. After the EUV light is emitted, the ratio of the three Sn states (fragments, neutral atoms, and ions) is important from the view point of debris mitigation. If all the Sn atoms are ionized, all the Sn ions can possibly be guided along the magnetic flux. Also, some neutral atoms can be guided and trapped by charge exchange with ions.14) In reality, however, not all the Sn atoms and ions can be trapped in the magnetic field. Accordingly, our system is also equipped with a chemical etching mechanism. With this mechanism the remaining Sn atoms that could not have been trapped in the magnetic field and deposited on the collector mirror surface and other place such as view ports are removed from the surface of the collector mirror and of some view ports.(Fig.11) We have investigated behaviours under various conditions to optimize Sn debris mitigation parameters in the compact EUV generation tool. 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 as we described in Section 3-2.

The amount and the distribution of the Sn neutral atoms after the pre-pulse laser irradiation in a certain magnetic field were observed with the Laser Induced Fluorescence (LIF) method. The Sn atoms are excited by a third harmonics of a narrow-band Ti:sapphire laser that 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. Two-dimensional atom distributions are obtained with a thin line-profiled laser beam probed from a direction perpendicular to the surface of the Sn target. The LIF imaging for the Sn atoms has several advantages, selectivity of species, high sensitivity, 2 -dimensional imaging with a sheet laser beam.Fig. 13 shows the result of the LIF measurements. When there is no main CO_2 laser irradiation, the neutral atoms and the fragments are observed. With the CO_2 laser irradiation, however, no neutral atoms and fragments are observed in these pictures.

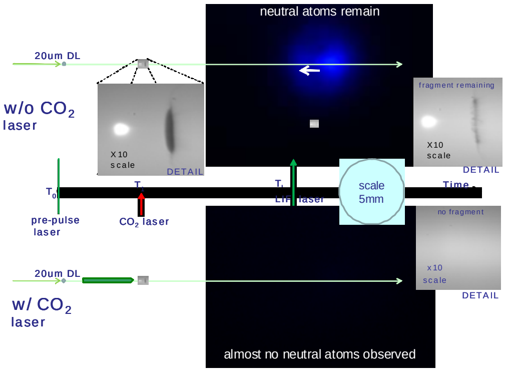

Fig.13 LIF measurement result

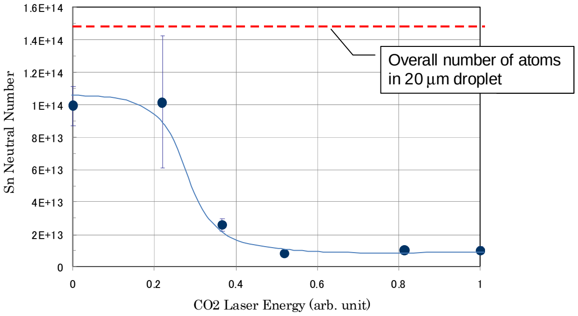

Fig.15 Ionization rate vs. CO2 laser power

This ratio changes with CO_2 laser pulse energy, as shown in Fig. 15. This data indicates that when CO_2 laser energy is above a certain energy level, almost all the Sn atoms in the Sn droplet are ionized under this irradiation condition. This is a very good indication, because this means that Sn ionization rate stays constant when CO_2 irradiation energy exceeds a threshold energy level. Accordingly, the debris mitigation system works stably for an extended operating time in the system. Also, we measured the ion distribution with the faraday cup measurement$^{15)}$ with/without a magnetic filed.

3.4 Driver pulsed CO_2 laser system

The pulsed Master Oscillator Power Amplifier (MOPA) CO_2 laser system has 20 nsec pulse duration (FWHM) and 20 kW average output power at 100 kHz repetition rate, which are optimized for Sn plasma generation.$^{16)}$ Also, the system are shown in Fig. 16. The hybrid CO_2 laser system consists of a short-pulse high-repetition-rate master oscillator (master-OSC) and multi-stage cascade amplifiers. The master-OSC laser is a Q-switched, 20 nsec, single P(20) line, RF-pumped waveguide CO_2 laser. The RF-excitation is a commonly employed scheme in axial flow or diffusion cooled slab or waveguide configurations, allowing a high repetition rate in pulsed operation by a well designed amplification system, for high repetition rate plasma generation. The commercial cw-CO_2 amplifiers are used as the amplifiers with some modifications. The laser system is operable from low duty mode (2 %) to full duty mode (100 %). The targeted specifications of this laser system are following; The master-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 one is OSC-AMP that amplifies the pulse energy. The pre-amplifier (pre-AMP) amplifies the pulse from 150 W to 3.0 kW (30 mJ, 100 kHz) output level with a slab-type discharge chamber. The main-amplifiers (main-AMP) further amplify the pulse from 3.0 kW to 20 kW (200 mJ, 100 kHz) output level with two sets of fast gasflow-tube-type discharge systems.

Fig.16 Hybrid CO_2 laser system

The temporal laser pulse profile of the amplified output is 20 nsec and the pedestal component has been confirmed at less than 10 % of the total output power. There is beam distortion in the active gas medium during amplification, but the thermal deformation in the solid optical components inside the beam delivery system seems to be the major source of the beam quality degradation. The sufficient cooling and careful optimization of the material would reduce these effects.16) Based on the engineering data of the ETS and the small experimental device, now we are developing our first generation HVM light source, GL200E, in our facilities. In 2011 we achieved 7W EUV clean power at I/F with 90kHz operation with 30% duty cycle (Fig.18). Our final target 250W is a challenge to enhance CO_2 laser power from 13 kW to 20 kW and CE from 3 % to 5 % under Sn debris free operation. However there were two big issues which limited log-term operation. One is long-term stability of Tin droplet, the other is limit of CO2 laser under 7kW output caused by parasitic oscillation.

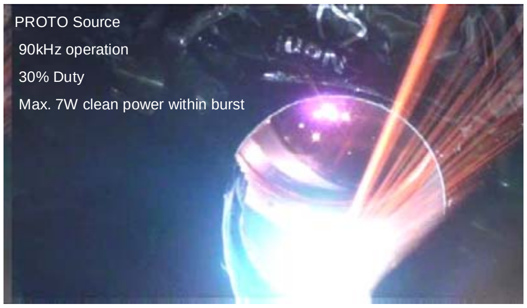

Fig.18 Picture of proto EUV source operation (2011)

4. Latest and Future technology development

4-1 . Latest status of GL200E development

This year 2012, we concentrate to solve these two issues17). We have find out the solutions. One is dramatic improvement of long-term stability of droplet generator. We improve Tin material and contamination originated from assembling process. We achieved more than 90h stable droplet generation (Fig.19). The other is CO2 laser power from 6kW to 9kW (Fig. 20). We improve unnecessary parasitic oscillation by optical modulator.

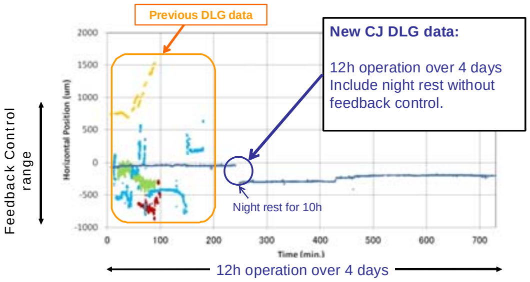

Fig.19 Improvement data of droplet generator

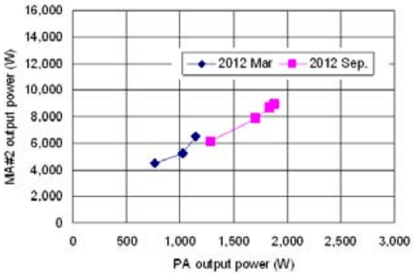

Fig.20 Improvement data of CO2 laser power

Combination of these two improvements on new improved EUV chamber (Proto-2) enables stable EUV emission. EUV burst operation data in Fig.21 shows stable average 10.2W(clean power @ I/F) EUV emission and maximum 20.3W(clean power @ I/F). We will increase the power level step by step in next couple of quarter.

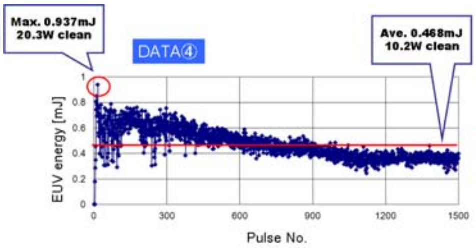

Fig. 21 EUV burst operation data

4-2 . Future technology for HVM development

Recently the CE of 4.7 % with the 20 μm diameter droplet has been demonstrated by optimizing the pre-pulse laser conditions as shown in Fig. 22 (red dot) with small experimental device. We have thus obtained the way to reduce the debris with the use of the 20 μm diameter droplet target without the degradation in the CE. These basic studies have contributed to the development of the high-power production machine and to the basic design for further EUV power scaling together with theoretical calculations. This phenomena is explainable with difference of pre-pulse expansion mechanism of ns-pulse and ps-pulse.

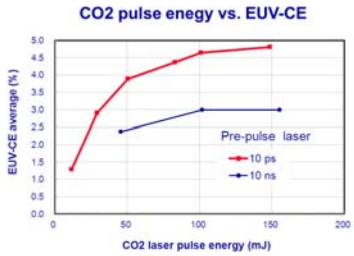

Fig.22 Higher Ce experiment with ps pre-pulse

By small experimental device clarify CE (Conversion Efficiency) improvement, with <20µm droplet we found the region where CE 4.7% average with pico second pre-pulse, and perfect vaporization are simultaneously possible. As shown in Fig.24 high CE technology enables 250W EUV source with 20kW CO2 laser. Furthermore higher power CO2 driver laser technology is also on going in Japan. For >500W EUV source, new 40kW CO2 laser amplifier development project started co-operation with Mitsubishi electric and Gigaphoton (Fig.25) [18] .

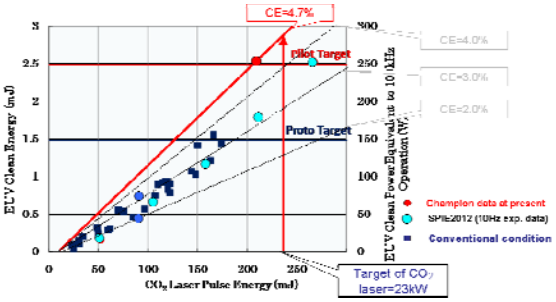

Fig.24 CO2 laser power vs. EUV power at high Ce

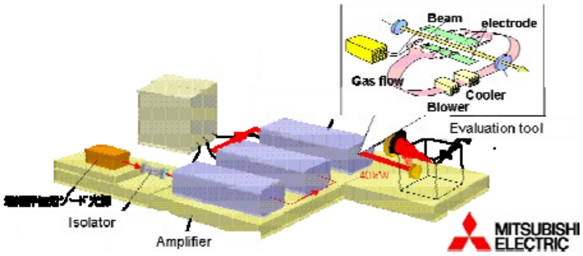

Fig.25 Higher power CO2 laser development schematic

5. Conclusion

We have reported the data since 2010 from the first LPP light source system "ETS" device and Proto system. We demonstrated from these experiments and Small size experiment about following three key engineering items are essential.

(1) High CE from CO2 laser to EUV light.

(2) Very small (<20µm) Tin droplet generation

(3) Stable high power pulsed CO2 laser.

Also combination of CO2 laser power and droplet generator improvements on new EUV chamber (Proto-2) enables stable EUV emission. EUV burst operation data showed stable average 10.2W(clean power @ I/F) EUV emission and maximum 20.3W(clean power @ I/F) was demonstrated with fully facilitated EUV source.

We are improving and engineering our system. Furthermore we have investigated the EUV plasma generation scheme by small experimental tool. We have proposed new double laser pulse irradiation method to generate LPP plasma efficiently. At this moment we have found the operation condition for obtaining CE of 4.7% by ps-prepulse. And also we report further higher power amplifier (>40kW) development project co-operate with Mitsubishi electric cooperation. Considering art of present technology, future potential technology and market situation. Gigaphoton assumes the target of shipment of "Gigaphoton's real pilot" maybe 2015.

6. Acknowledgement

This work was partly supported by the New Energy and Industrial Technology Development Organization (NEDO), Japan.

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