1st generation Laser-Produced Plasma source system for HVM EUV lithography

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ABSTRACT

The 1st generation Laser-Produced Plasma source system "ETS" device for EUV lithography is under development. We report latest status of the device which 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. Maximum power is 100W (100kHz, 1mJ EUV power @ intermediate focus), laser-EUV conversion efficiency is 2.3%, duty cycle is 20% at maximum. Continuous operation time is so far up to 3 hours. Debris is efficiently suppressed by pre-pulse plasma formation and magnetic field mitigation system. Long-term performance is now under investigation. Also future plan is updated.

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

1. INTRODUCTION

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). 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. 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.

Up to now we have reported progress of the each component technology. From 2009 we have been constructing system demonstration device: ETS -- "Engineering Test Stand" for the purpose of performance demonstration with all of component technologies integrated. In this paper we introduce latest performance of this ETS device.

2. ETS-DEVICE

The purpose of the ETS is:

- The 1st generation integrated LPP system which demonstrates 100W (average 75W) system operation.

- Prove technical concept with real data with integrated system. The concepts are pre-pulse target heating, mass limited target, magnetic mitigation and mirror cleaning technologies.
- Clarify the engineering issues of component and find solution for the multi 10kW high power CO_2 laser, EUV chamber (collector mirror, droplet generator, etc.)
- Feedback engineering data to product design.

We show the out look of ETS system in figure 1. The system mainly consists of the following major 5 sub-systems.

(1) EUV chamber system

(2) High power hybrid CO_2 laser system

(3) Pre-pulse laser system

(4) Magnetic mitigation system

(5) Control system

Detail of these 5 sub-systems is explained from next section.

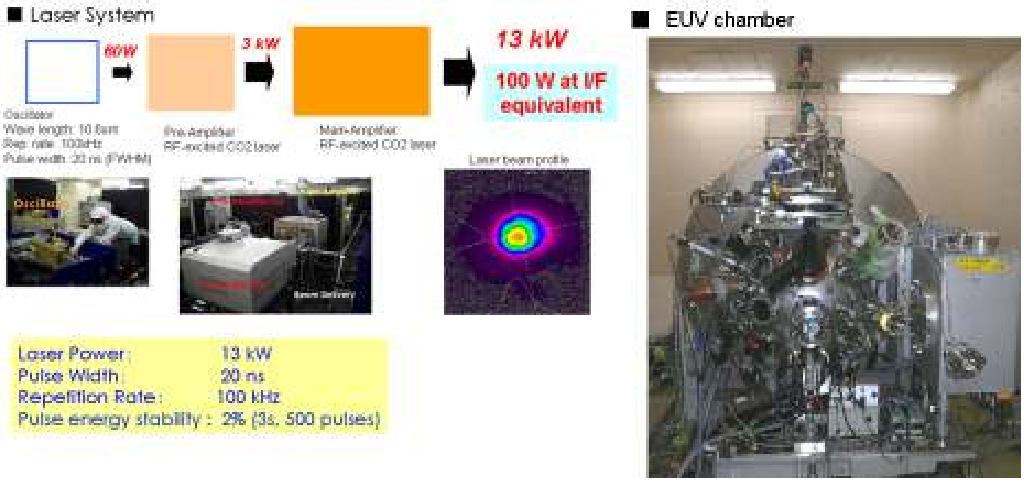

Fig.1 Outlook of ETS LPP-EUV source system

The target specification of ETS device is shown in table 1. 100W power corresponds to throughput of 100WPH on EUV exposure tool at $5mJ/cm^2$ sensitivity resist in lithography process.

Table 1 Target specification of ETS device

EUV model	ETS device
EUV Power (@I/F)	> 100W
EUV Pulse energy (@I/F)	> 1 mJ
Max Rep. Rate	100 kHz
CO_2 laser system	10 kW (20ns, 100kHz, 100mJ)
Target material and shape	Sn droplet
Droplet size	60μm diameter
Plasma creation	Pre-pulse heating + Main pulse heating
Debris mitigation	Magnetic
C1 Mirror life	> 3 months

2-1 EUV chamber system

Figure 2 shows schematic of EUV chamber. 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.

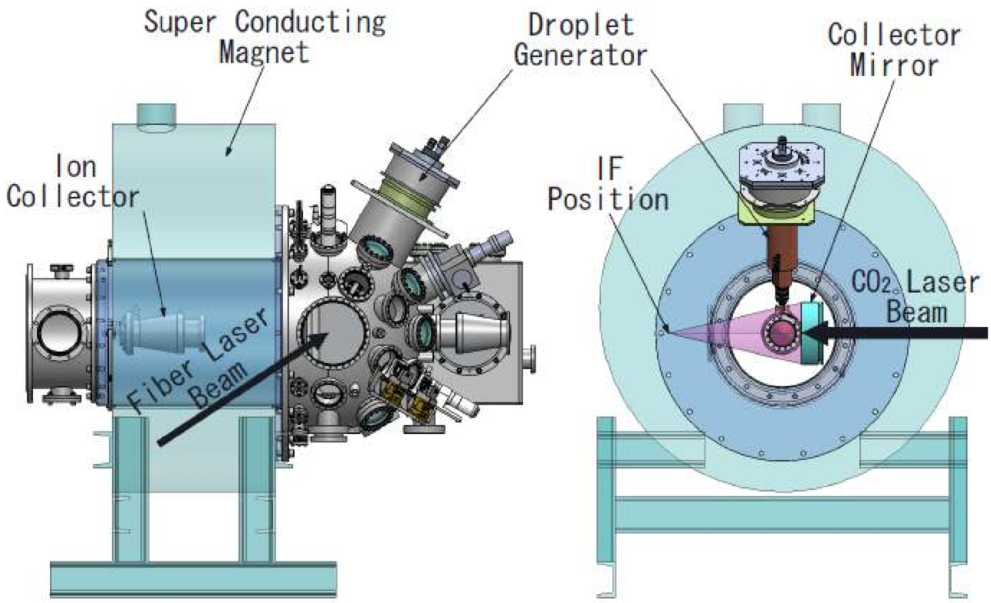

Figure 2 EUV chamber of ETS device

Tin droplets with various diameters and spacing are generated by changing the nozzle inner diameter and PZT frequency. The Tin supply tank is heated above the melting temperature of Tin, i.e. 232 ^{o}C. The liquid Sn jet is emitted from the nozzle by pressure control [5]. Generated droplet diameter is 60 μm at 400 kHz with 60 m/s injection velocity (Figure 3). Behavior of the droplet injection is usually not stable due to fluid dynamic fluctuation. Sufficient stabilization was achieved by an active feedback of the injector controller. Figure 4 and 5 shows the measured results of the droplet position stability. The measurement was at 100 mm from the nozzle. Long term stability of the droplet is another factor to guarantee the long term EUV IF power stability. Its spatial and temporal precision was stabilized by active feedback technique.

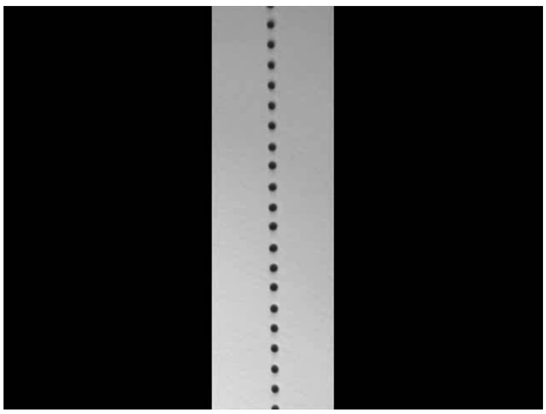

Figure 3 Picture of 60 μ m droplet train

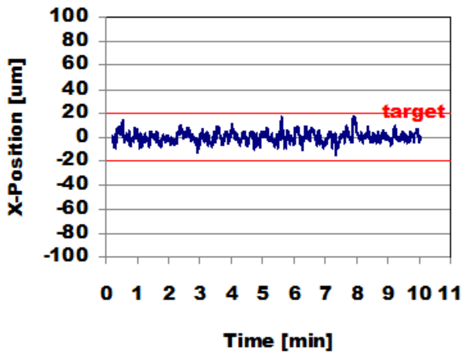

Fig. 4 Stabilization of droplet spatial precision

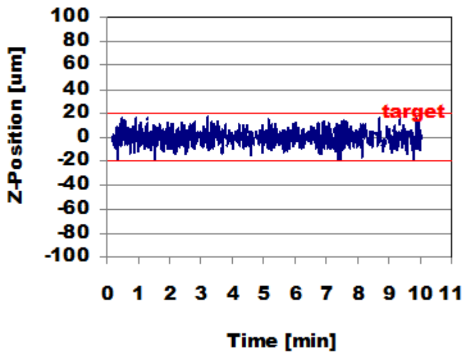

Fig. 5 Stabilization of droplet temporal precision

2-2 Hybrid CO_2 laser system

We have been developing a short pulse CO_2 MOPA (Master Oscillator Power Amplifier) laser system with 20 ns pulse width and 10kWaverage power at 100 kHz repetition rate (Champion data today is 13kW). Figure 6 shows the present laser system configuration. 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. The repetition rate can be tuned from 10 to 140 kHz. 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%).

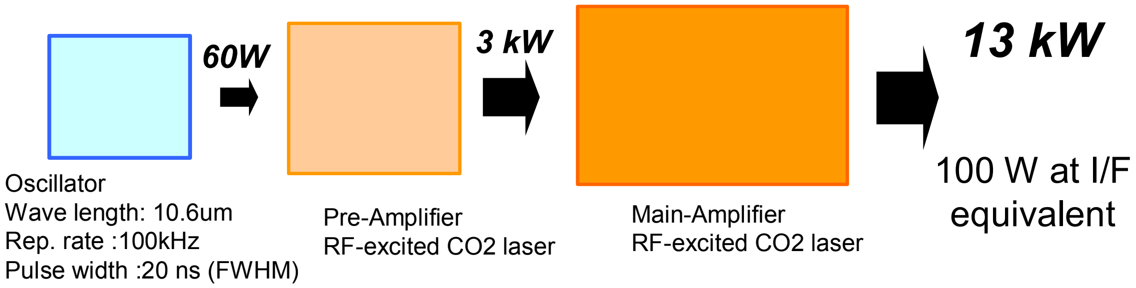

Figure 6 Configuration of the CO_2 MOPA system.

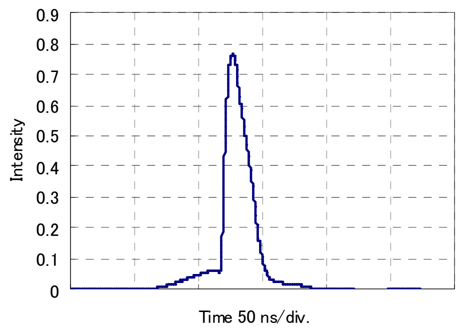

Figure 7 Temporal laser pulse profile

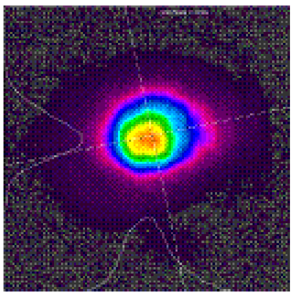

Figure 8 Spatial laser beam profile

Figure 7 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 source of the beam quality degradation. Enough cooling and careful optimization of the material reduces these effects. Figure 3 shows the measured beam profile at full power operation with beam quality as M^2 value of 1.1.

2-3 Magnetic mitigation system

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.

On the other hand, 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 produced 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] In other words, CO_2 laser plasma contains high amount of ions because of better laser light absorption by Tin plasma. These ions are able to be confined in plasma region by strong magnetic field. We call this scheme "Magnetic mitigation". 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. Magnetic plasma guiding was characterized by monitoring plasma current and shape in a large vacuum chamber with a maximum magnetic flux density. It was shown that Tin plasma flow was kept stable along the magnetic field line with a diameter of less than 10mm to the Tin collector. In figure 9, picture of magnetic field guided LPP plasma is clearly captured from the viewing port of EUV chamber. Plasma clearly flows along the direction of magnetic field.

Figure 9 Picture of magnetic field guided LPP plasma

Figure 10 shows the experimental data of magnetic mitigation of CO_2 LPP plasma with solid target. There was no deposition on the direction across the magnetic field. While on the direction along the magnetic field, all of the Tin deposited on the witness plate (Figure 10). This dada promises the effectiveness of our magnetic mitigation concept to CO_2 LPP Tin plasma[7,8].

Even ion is perfectly shielded by magnetic field, a certain percentage (a few 0.1%) of neutral atoms leak from magnetic field. In order to clean this small leakage, we find good etching source. Our calculation indicates the combination of magnetic mitigation and etching can maintain clean surface on C1 mirror by the "in situ cleaning".

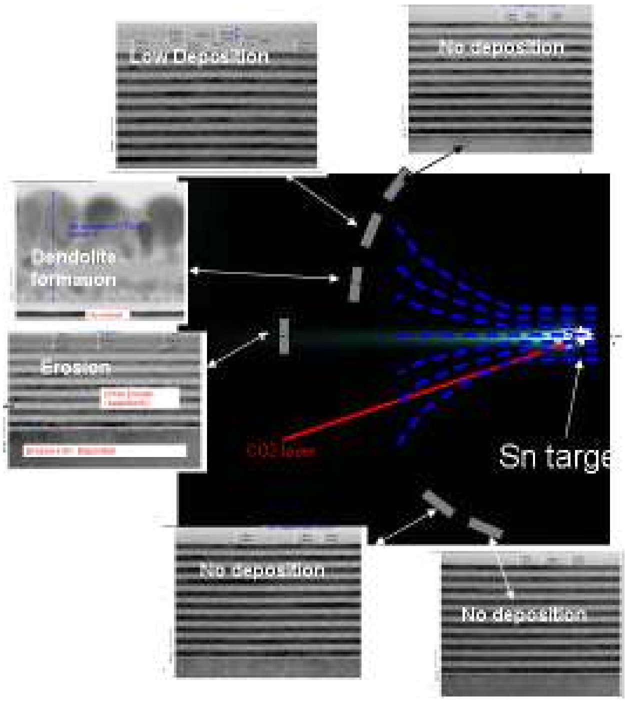

Figure 10 Magnetic mitigation result on ETS

2-4 Pre-pulse laser system

In the case of solid Tin target surplus material remain on the solid target surface. However, in the case of droplet target, surplus material is splashed by the reaction force of plasma jet. Therefore we use pre-pulse laser to smash the Tin drop in advance. The smashed target is easy to ionize because of larger surface compared with single droplet. For this pre-pulse we use Fiber laser.

In Figure 11, LPP plasma components coming from droplet are shown. That is, after pre-pulse laser irradiation ion cloud created (green area). The ion cloud pushes the liquid drop. The pushing force smashes the liquid drop, then create fragments (gray part) and neutral atom flux (bleu area). The main CO_2 laser heats these three expanding components after several μs to several 10μs.

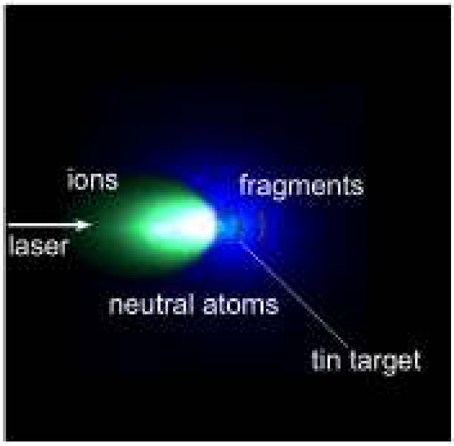

Figure 11 Components coming from pre-pulse irradiated droplet (image)

2-5 Control system

For the uniform exposure, dose stability of EUV source is important. For the realization of this stability several control loops are implemented. In ETS device we are experimentally proving the performances of control (1)-(4) below:

(1) Droplet position control (position, direction, timing)

(2) Main laser beam control (position, direction, power)

(3) Pre-pulse laser beam control (position, direction, power)

EUV mirror control (position, direction)

3. PERFORMANCE

Latest performance summary is shown in Table 2. Continuous operation was tested with all component technologies to evaluate the effectiveness of the system. We observed 100W EUV power at 20% duty cycle, measured by flying circus calibrated instruments. CO_2 laser was kept as 8 kW at 20% duty cycle with continuous magnetic field. The average conversion efficiency was 2.3%. The operation was continued for >1 hours. Plasma flow along the magnetic filed line was observed.

Tabele 2 Performance data of ETS-device (January 2010)

	Last data (09/10)	**Latest (10/01)**
Average power (@I/F)	**2.5 W**	**14 W**
Brightness (@I/F)	**25 W**	**69 W**
Duty cycle	**10%**	**20%**
Max. non stop op. time	**3 hr**	**>1 hr**
Experiment time	**7 hr**	**-**
Average CE	**1.5%**	**2.3%**
Dose stability (simulation)	-	(+/- 0.15%)
Droplet diameter	**60 μ m**	**60 μ m**
CO2 laser power	**5.0kW**	**5.6kW**

Figure 12 shows the measured long term EUV output data without feed back control. It shows relatively good stability even under open loop operation. And we estimated closed loop feedback stability over 50 pulse accumulation with running window. Result is shown in Figure 13-1,13-2. These data show excellent stability of +/- 0.26 % which meets requirement for lithography process. Next step of our ETS-device is experimental demonstration of log-term stability and debris mitigation free operation.

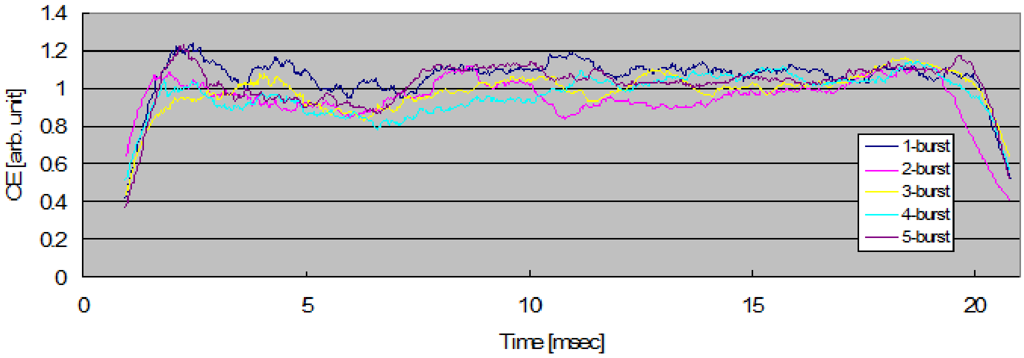

Figure 12 EUV light data (100W at 20% duty cycle; ON/20ms:OFF/80ms)

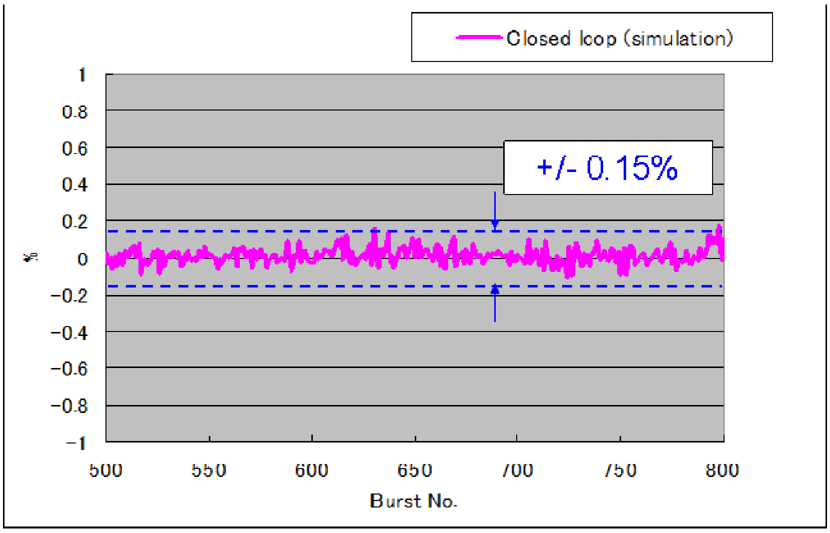

Figure 13-1 EUV stability data (closed loop simulation)

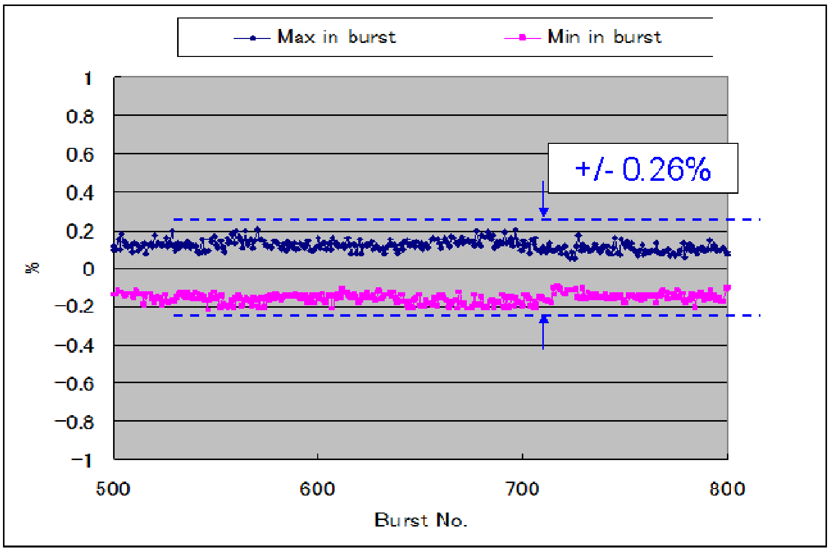

Figure 13-2 EUV dose data (closed loop simulation)

4. FUTURE PLAN

The road map of Gigaphoton LPP EUV source is shown in Figure 13. After ETS device we have a plan to develop 2nd generation GL200E in 2012. One year before we will develop 100W device as GL100E-proto with almost the same configuration of GL200E. After 2014 we will release >400W device named GL400E.(Figure 14)

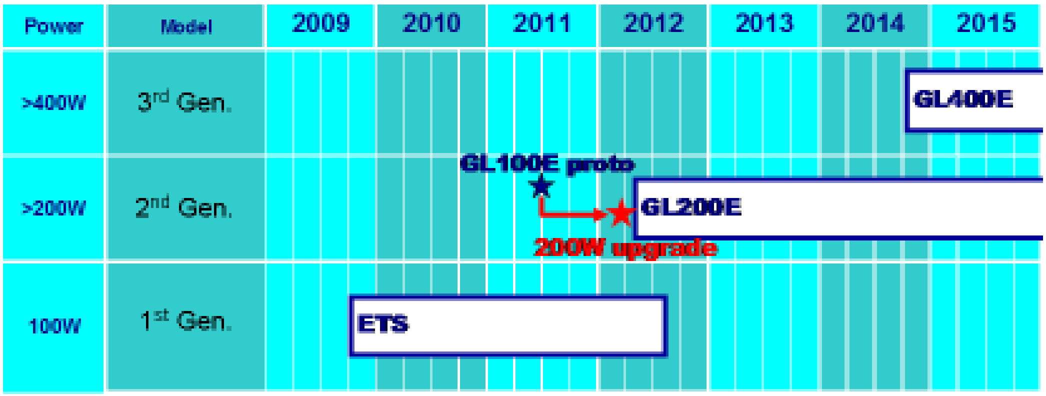

Figure 14 Road map of Gigaphoton LPP EUV source

5. CONCLUSION

The 1st generation Laser-Produced Plasma source system "ETS" device for EUV lithography is under development. We report latest status of the device which 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. Maximum power is 100W (100kHz, 1mJ EUV power @ intermediate focus), laser-EUV conversion efficiency is 2.3%, duty cycle is 20% at maximum. In the background we have steady progress on the CO_2 laser produced Tin plasma method for HVM EUV light source, high duty operation of pulsed CO_2 laser without any degradation of fine beam quality. Also improved stability of the Tin droplet injector enables continuous plasma creation. Magnetic field collects the injected Tin ions and guides them into a Tin collector. Continuous operation time so far is 3 hours. Debris is efficiently suppressed by pre-pulse plasma formation and magnetic field mitigation system. Long-term performance is now under investigation. Also future plan is updated.

6. ACKNOLEDGEMENT

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