Introduction of Products

Short wavelength light source for semiconductor manufacturing: Challenge from excimer laser to LPP-EUV light source

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The remarkable progress of the latest IT technologies are supported by miniaturization of semiconductor devices such as CPUs and memory chips. Optical lithography technology used in semiconductor manufacturing processes has contributed to this miniaturization. Today, excimer laser which emits a beam of ultraviolet light is used as the light source. As a result of making efforts to meet the market's demands for laser with shorter wavelengths and higher outputs, the Gigaphoton company has been holding top share in the global market of excimer laser systems since 2014. However, strong requests for further miniaturization are still growing, and the EUV (Extreme Ultra Violet) light source, which can emit plasma light of a shorter wavelength, is strongly desired for practical use.

Gigaphoton has been researching and developing EUV light source systems since 2002, and succeeded in developing a near-product prototype. By using original technologies, a system having high efficiency and high output that can meet market demands has been attained. The current issue is to establish a production line that can be run stably for prolonged periods of time at the semiconductor factory by improvement of the engineering aspects. The development is under progress, aiming to start delivery in a few years.

Key Words: *Lithography, excimer laser, EUV, plasma, semiconductor*

1. Introduction

Despite the declining trend of the semiconductor manufacturing industry in Japan over the past decade, the global demand for semiconductor device has steadily expanded at an annual rate of about 4%. In the lithography process with reduced projection exposure equipment which is the heart of semiconductor microfabrication technology, KrF excimer laser is used for the design rule of miniaturization around 180 nm node or less, ArF excimer laser is used as mass production equipment for 100 nm or less, and ArF immersion lithography technology is applied for 100 nm and beyond in the advanced mass production fab. Beyond the 45 nm, the mass production fab of NAND flash memories of 32 nm and 22 nm, which are currently the mainstay, has introduced lithography equipments that realize double patterning technology in ArF immersion. For the subsequent 16 nm, EUV lithography that uses the extreme ultraviolet light (EUV) of 13.5 nm has been considered promising, but due to delay in improving the light source output, it fell out of mass production technology (2012). At present, mass production with ArF liquid immersion lithography combined with multi patterning has begun. As of 2016, the market size of lithography excimer lasers exceeds 80 billion yen/year and it is growing steadily.

In the immersion lithography technique, a liquid having a large refractive index is filled between the objective lens of the exposure tool and the wafer to shorten the apparent wavelength to increase the resolving power and the depth of focus. Resolution and depth of focus by immersion are expressed by the following equations called the Rayleigh's equations. That is;

Resolution = $k_1 (\lambda/n) / \sin\theta$

DOF = $k_2 \cdot n\lambda / (\sin\theta)^2$

k_1, k_2: experimental constant factor

N: Refractive index, λ: Wavelength

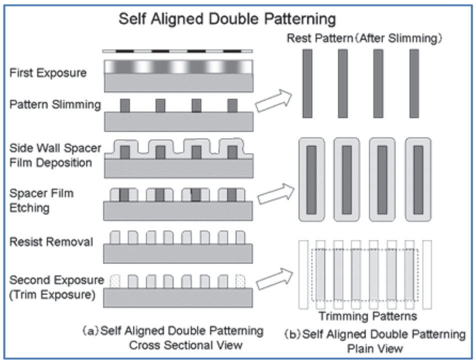

Fig. 1 Example of double patterning technology[1)]

However, k_1 in this formula cannot be lowered to 0.25 or less by a single patterning. Therefore, double patterning technology has attracted attention and has been practically used. **Fig. 1** shows an example of a basic method of double patterning. Doubling the spatial frequency of the pattern formed by the first exposure is called a double patterning technique[2)], and recently even triple patterning and quadruple patterning have been examined for introduction to cutting-edge processes.

Fig. 2 ArF excimer laser GT64A for mass production

Currently, in mass production factories, narrow band ArF excimer lasers[2)] are used for ArF immersion lithography and multiple patterning processes. Gigaphoton Inc. is mass-producing light sources "GT series" for ArF lithography. Since the release of ArF laser GT40A with unique injection lock system in 2004, Gigaphoton then released GT60A in 2005, and the series has continued to evolve to GT64A with 120 W output[3)] (**Fig. 2**). The "GT series" has been highly appreciated by end users for its high performance (Availability > 99.6%) while the appearance of EUV has been delayed. As of the end of 2015, this series boasts over 400 cumulative shipments to world's leading users. Gigaphoton has been sluggish due to the declining trend of the semiconductor industry in Japan since Lehman shock. However, it recently has been highly appreciated by overseas users for its superiority of energy saving performance, and its global market share was 52% in 2014 and 63% in 2015 (**Fig. 3**). Gigaphoton has grown into a light source manufacturer shipping the world's highest number of excimer lasers. Meanwhile, in a state-of-the-art market, cost of transistors has been elevated because the multiple patterning involves complicated processes, an advent of EUV lithography technology is highly expected.

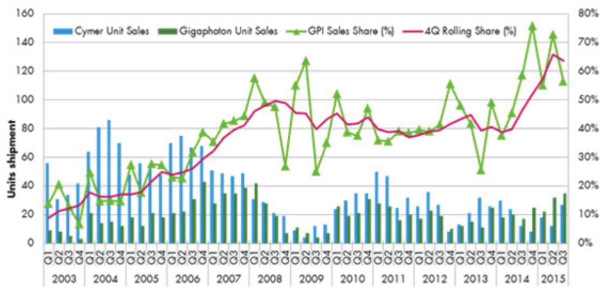

Fig. 3 Worldwide market share of excimer laser for lithography (Data source: Gigaphoton)

2. EUV Lithography

2.1 EUV Lithography and Development Background

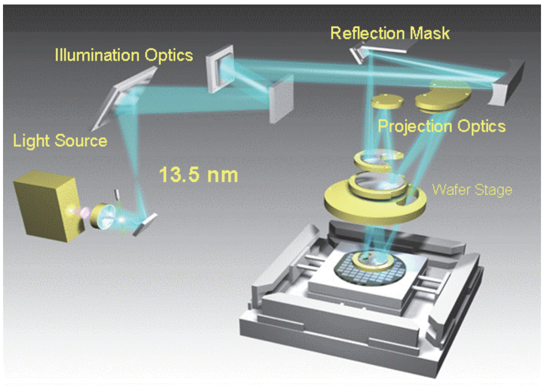

Fig. 4 Conceptual diagram of EUV lithography exposure tool

Reduced projection lithography using EUV light with a wavelength of 13.5 nm and catoptric optical system (reflectance of about 68%) is a technology originated in Japan by NTT's Kinoshita et al.[4] in 1989. It can realize a resolution of 20 nm or less using a catoptric optical system with NA = 0.3. This is said to be the ultimate optical lithography (**Fig. 4**). However, 13.5 nm light is strongly absorbed by gas. It therefore can propagate only in high-vacuum container or container filled with dilute high purity gas. Furthermore, since the mirror reflectance is only 68%, if high NA reduced projection is performed using 11-mirror system, only 1.4% of the light will reach the exposure surface. In mass production, in order to realize productivity of 100 WPH (wafer per hour) or more for 300 mm wafer, the light source requires the output of 250 W or higher.

Table 1 Wavelength, refractive index, and resolving power of immersion lithography technique

	R (K1=0.4) nm	n	medium	λ / n *nm*	NA	Power
KrF dry	124	1	Air	248	0.8	40
ArF dry	103	1	Air	193	0.75	45
F_2 dry	84	1	N_2	157	0.75	–
ArF immersion	40	1.44	H_2O	134	1.35	90
EUV (λ=13.6nm)	18	1	Vacuum	13.6	0.3	>250
EUV (λ=13.6nm)	9	1	Vacuum	13.6	0.6	>500
EUV (λ= 6.7nm)	4.5	1	Vacuum	6.7	0.6	>1000

This insufficiency in the output of light source is causing delay in the advent of EUV lithography. However, due to the magnitude of its ripple effect, great R & D expenditure is being investigated worldwide as the promising technology in the next generation 10 nm node and beyond. The relation between the light source wavelength, NA of optical system, and the resolving power is shown in **Table 1**. At present, a resolution of about 18 nm can be obtained by combining an optical system of NA = 0.3 with a wavelength of 13.5 nm. Currently, development of the next-generation catoptric optical system with NA = 0.55 or higher has been developed with anamorphic optics with less light loss and different longitudinal and lateral magnifications. However, it is said that the next generation system will require 500 W or higher output because of the dropping of resist sensitivity due to miniaturization[5]. In the future, if a combination of a light source of about 1000 W in the vicinity of 6.7 nm wavelength and an optical system with NA = 0.6 can be realized, resolution of 5 nm and beyond will be possible (**Table 1**).

2.2 Current Development of Exposure Tool and Its Market in the World

At present, the development of cutting-edge mass production lithography tool for EUV lithography in the world is under the initiative of ASML Corporation in the Netherlands. In the early days (around the year 2000), some small-field exposure tools were prototyped by some exposure tool manufacturers. Then, in 2006, the full-field α-Demo-Tool, which was a full-fledged lithography tool leading to current tools, was developed by ASML. This tool has a discharge-produced plasma (DPP) light source of 10 W class (design value), and delivered to IMEC in Europe and Albany Laboratories of SEMATECH in the U.S.[6]. In 2009, ASML developed the EUV β machine NXE-3100 equipped with a 100 W light source (design value)[7]. Six units in total, one equipped with an XTREME's DPP light source and five equipped with Cymer's laser-produced plasma (LPP) light sources, were shipped. Initially ASML aimed to realize mass production precursors equipped with a 100 W light source, but as of 2012 the light source output was sluggish at 7 to 10 W and became a bottleneck in EUV lithography mass productivity verification.

On EUV γ machine NXE-3300 in 2013, they aimed for productivity of 200 WPH or more with EUV light source of 250 W (design value)[8]. The light source, however, initially operated at 10 W level. ASML announced a plan to improve the light source to 80 W or more until 2015. The units for TSMC[9] and Intel Corporation[10] were modified in the latter half of 2014 and it was reported that a simulated operation with 80 W succeeded. In 2015, the modification to the 80 W level light source and its practical operations were finally realized in some users, and achievement of 1000 WPD (Wafer Per Day) was reported. As of 2016, achievement of 1500 WPD with 125 W light source at a laboratory of lithography tool manufacturer has been reported[11].

On the other hand, manufacturers of light source are facing severe situation due to delays in commercialization - increased cost of EUV light source development puts the management under pressure. Cymer, LLC. who preceded with the EUV β machine was acquired by ASML in June 2013 due to heavy development cost. Furthermore, XTREME who preceded with the α-Demo-Tool was dissolved in May 2013. Gigaphoton has been undertaking full-fledged development independently from 2012, but the product is still in the middle of the development phase. It can be said that the light source manufacturers are literally within the turbulent "death valley".

3. Details of High Power EUV Light Source and its Concept

Fig. 5 shows a conceptual diagram of the EUV light source of Gigaphoton. At present, excellent characteristics of this method are recognized, and it became the mainstream method of high power EUV light source in the world. In order to efficiently generate EUV light, it is necessary to generate the plasma of about 300,000 K from the principle of black body radiation. To generate this plasma, approaches have been made in two ways.

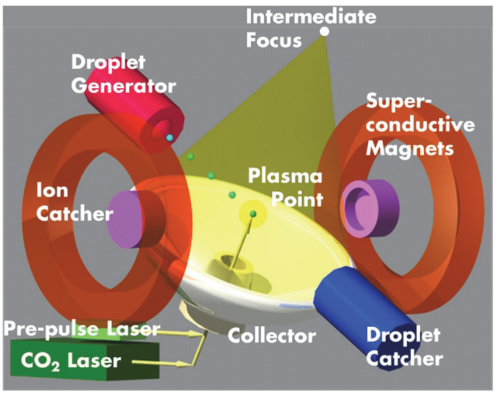

Fig. 5 Concept of EUV light source of Gigaphoton Inc.

One is a Discharge Produced Plasma method using pulse discharge[12], and the other is a Laser Produced Plasma method that irradiates a pulse laser to a target. These researches began in the end of 1990s, at some institutes such as EUVLLC[13] in the U.S. and the Fraunhofer-Gesellschaft in Europe.

In Japan, the Research and Development Partnership, Extreme Ultraviolet Lithography System Development Association (EUVA) was established in 2002 and the development of EUV lithography and its light source technologies started. The authors have participated in this organization and, from the beginning, we have pursued a scheme to irradiate pulsed CO_2 laser to the target material to generate high temperature plasma[14]. Then, triggered by the measurement result[15] of Professor Okada (Kyushu University) for the MEXT's leading project started in 2003, we convinced that the LPP method using CO_2 laser as the driver laser will become the promising, and started the development of this method in 2006. For the CO_2 laser system, we adopted our own MOPA system, which uses reliable industrial CW-CO_2 lasers as amplifiers. In this system, hight repetition pulse light (100 kHz, 15 ns) generated in the pulse oscillator is amplified by the multiple CO_2 amplifiers[16]. The target is liquid Sn droplets of about 20 μm diameter generated by heating Sn to the melting point and the droplet generation technology has achieved stable ejection. The EUV collector mirror is installed in the vicinity of the plasma and reflects and condenses the EUV light to the illumination optical system of the exposure tool. Although high-speed ions generated from this plasma cause sputtering damage on the multilayered film on the mirror surface, a unique ion control technology using magnetic field is applied for prevention and mitigation of this damage.

4. Recent Progress of High Power EUV Light Source Development

4.1 Improvement of Conversion Efficiency

Yanagida et al. found that a high conversion efficiency (>3%) could be obtained by optimizing the parameter of the generated plasma by the double pulse method in which the YAG laser and CO_2 laser were irradiated on the Sn droplet with a time lapse[17]. This result could be well explained by Nishihara et al's theoretical calculation resulting the improvement of conversion efficiency[18]. Furthermore, in 2012, we optimized the pulse width of the YAG pre-pulse laser and realized an epochal efficiency improvement of about 50%. By changing the pulse width of the pre-pulse from about 10 ns to about 10 ps and then heated by the CO_2 laser pulse, conversion efficiency was improved from 3.3% to 4.7%. More recently, the conversion efficiency of 5.5% was experimentally verified (**Fig. 6**). This is an epoch-making, world's highest record. If this efficiency can be realized at the product level, an EUV output of 250 W can be achieved with an average output of 21 kW pulse CO_2 laser and an EUV 500 W can be realized with a 40 kW pulse CO_2 laser[19].

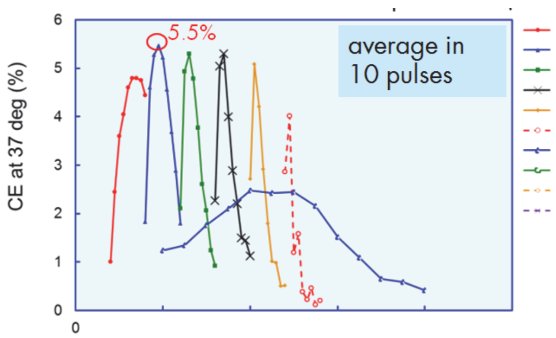

Fig. 6 EUV conversion efficiency
(EUV light / CO_2 laser)

4.2 Development of High Output CO_2 Laser[20)21)]

In order to achieve EUV output of 250 W, a cooperative project with Mitsubishi Electric Corporation was carried out under the support of NEDO in 2011 and 2012. Using a pulse oscillator made by Gigaphoton and a 4-stage amplifier made by Mitsubishi Electric, an output of CO_2 laser amplifier exceeding 20 kW at a pulse duration of 15 ns, 100 kHz was demonstrated (**Fig. 7**).

Fig. 7 CO_2 amplification experiment device
(provided by Mitsubishi Electric Corp.)

Based on this achievement, this amplifier was shaped to a practical level and amplification experiment of high power CO_2 laser was carried out in 2014. According to the test results, the output conventionally limited to 10 kW was improved up to 20 kW. Furthermore, the amplification efficiency was improved by 10 to 15% in the amplification experiment using the multiple oscillation lines of CO_2 laser and 23 kW was successfully generated by the Proto #2 unit. Currently, a system in which four units of this amplifier are arranged in series is under development as a driver laser of a pilot light source (Section **5.**).

4.3 Droplet Generator

A droplet target system is applied for the light source. First, tin is heated to the melting point (231.9°C) or higher to liquefy it. By ejecting this liquefied tin through a narrow nozzle hole droplet target is supplied to the plasma generation position. In order to stably provide droplet targets, the authors have made many technical improvements. As a result, recently a droplet target with diameter of about 20 µm can be generated at 100 kHz. Droplet targets with excellent position stability can be generated at a droplet speed of 90 m/s for 200 hours or more in running time.

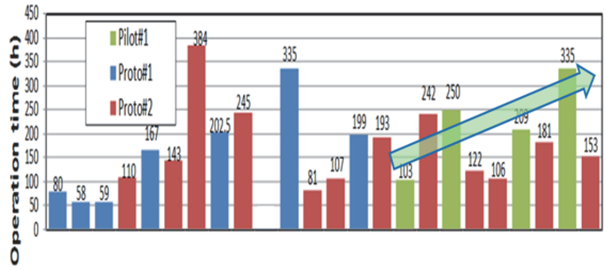

Fig. 8 Change of droplet continuous generation time

4.4 Magnetic Field Debris Mitigation Technology[22)]

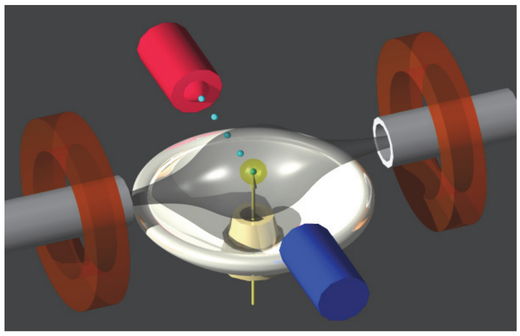

Fig. 9 Structure around the collector mirror

The tin liquid droplet is irradiated by the pre-pulse laser light and then by the carbon dioxide gas laser light to emit EUV light. After that, tin ions caught by the magnetic field are guided and discharged along the magnetic lines to the ends (**Fig. 9**). Currently, it has been proved that the ionization rate can be improved to 99% or higher by combining a 10 ps pre-pulse with a CO_2 laser as described in the previous section. On the actual device tests, deposition of Sn by back diffusion from the ion catcher was observed on the collector surface near the ion catchers (**Fig. 10**).

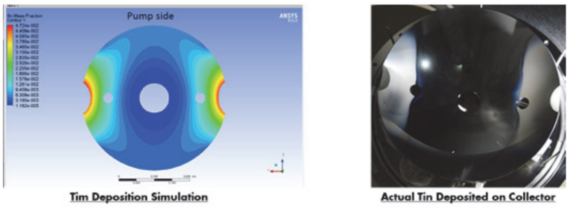

Fig. 10 Sn contamination of the EUV mirror section

On the other hand, it was confirmed by simulation that the debris was improved drastically by controlling the flow path of the etching gas (**Fig. 11**).

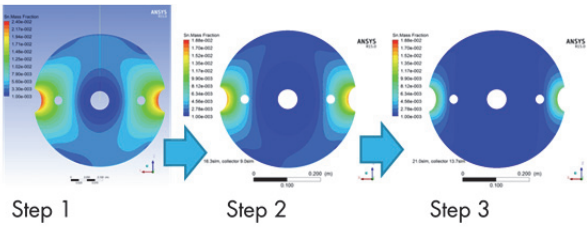

Fig. 11 Improvement of back diffusion from ion collector

In Proto #1 which has 10 W level output, it has succeeded in transmitting EUV light to EUV light irradiation part over 3 days.

4.5 High Output Experiment by EUV Light Source Device Prototype #2[23)24)]

Since 2002, Gigaphoton has been developing a number of EUV light source experimental devices and has been working on improving its technology; it produced ETS machine in 2007, Proto #1 in 2012 (**Fig. 12-1**), Proto #2 in 2014 (**Fig. 12-2**). Currently, the development of high power light source technology is promoted using this Proto #2. Since 2015, we have been developing Pilot #1 unit aiming to commercialize the light source unit in parallel with high power experiment (**Table 2**).

Table 2 Specifications of prototype Gigaphoton EUV light sources

Operational Specification Concept		Pilot #1 HVM readiness	Proto #2 Power scaling	Proto #1 Proof of concept
Target Performance	EUV Power	250 W	> 100 W	25 W
	CE	4%	3.5%	3%
	Pulse rate	100 kHz	100 kHz	100 kHz
	Output angle	62°upper (matched to NXE)	62°upper (matched to NXE)	Horizontal
	Availability	> 75%	1 week operation	1 week operation
Technology	Droplet generator	< 20 μm	20 μm	20 – 25 μm
	CO_2 laser	27 kW	20 kW	5 kW
	Pre-pulse laser	picosecond	picosecond	picosecond
	Debris mitigation	> 3 month	10 days	validation of magnetic mitigation in system

Fig. 12-1 Proto #1 EUV light source

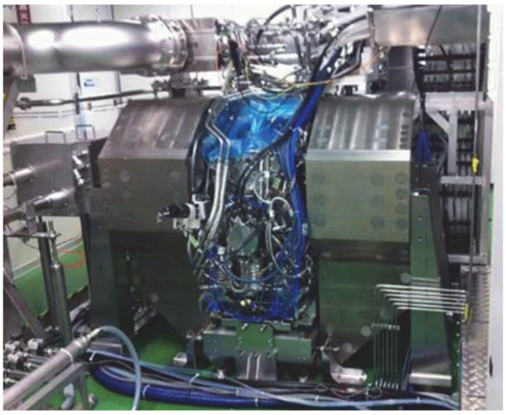

Fig. 12-2 Proto #2 EUV light source

Fig. 13 shows the progress of the improvement on the output of Proto #2 and the current performance of Pilot #1. It shows that from 2015 the output data has been rapidly improved with the improvement of engineering technology.

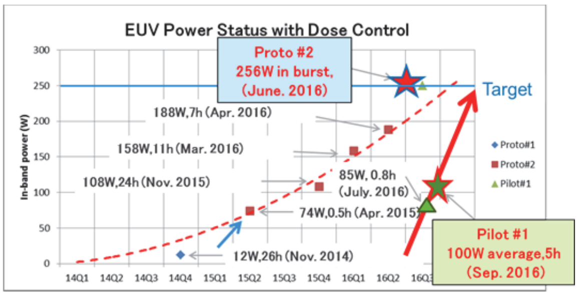

Fig. 13 Transition of output data of Gigaphoton's EUV light source devices

In June 2016, Gigaphoton succeeded in the operation exceeding 250 W for a short time (**Fig. 14**). We produced an output of 301 W (in burst) in the open loop, and succeeded in driving at 256 W in a closed loop in which feedback was applied and light quantity was stabilized. Also at this point, conversion efficiency CE = 4.0% was realized despite high power operation. However, the duty cycle of operation was 50% due to the restriction of Proto #2 equipment.

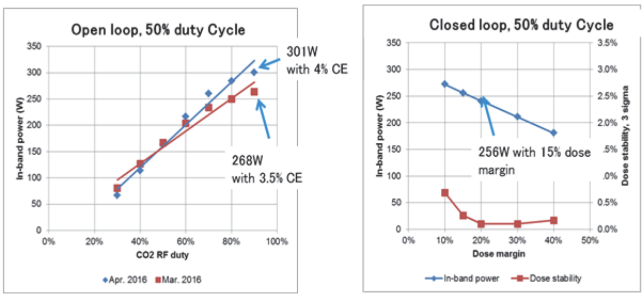

Fig. 14 250 W operation data of Proto #2

In addition, from the data of the system test of the same Proto #2, stable emission data (3σ < 0.5%) was confirmed in about 120 continuous hours at Duty = 40 to 50% simulating the exposure operation with the EUV output of 158 to 132 W (in burst) (**Fig. 15**).

Result:
In-band power: 158W–132W
Operation time: 119 h
Number of Pulse: >17.8 Bpls
Dose stability3σ: < 0.19 %

Condition:
Repetition rate: 100kHz
Duty: 40/50% *
Average power: 79W–52W
With dose control mode
* 10 kpls on/0.15 or 0.1s off

Fig. 15 Proto #2 EUV light source long-term operation data

5. Development of EUV Light Source Pilot System[24)]

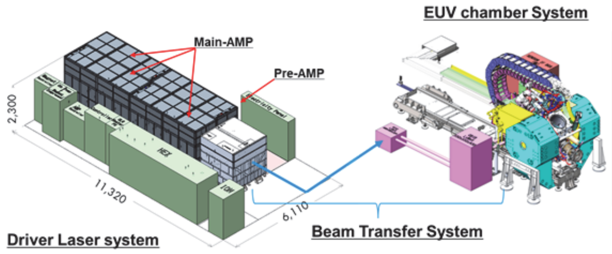

Fig. 16 250 W EUV light source unit GL200E-Pilot

Gigaphoton is aiming at realization and mass production of 250 W (@ I/F) EUV light source for mass production fab after the 12 nm node in 2017. **Fig. 16** shows an outline of the product type pilot unit (Gigaphoton GL200E-Pilot). A pre-pulse laser and a CO_2 laser for main plasma heating are arranged in the downstairs space called sub-fab, and a chamber for EUV generation is arranged on the clean room floor. The EUV generation chamber and the exposure tool are optically coupled. Inside this section, Sn droplets are irradiated with laser to generate EUV light. This facility was constructed in Gigaphoton Hiratsuka plant, and began full-scale operation from September 2016. An outline and the latest data of this facility are introduced below.

5.1 EUV Chamber System

Fig. 17 External view of EUV chamber system

Fig. 17 shows an external view of the EUV chamber system. As can be seen from the photograph, a vacuum chamber for generating EUV is inserted between a pair of superconducting magnets. The approximate size can be estimated from a person standing by.

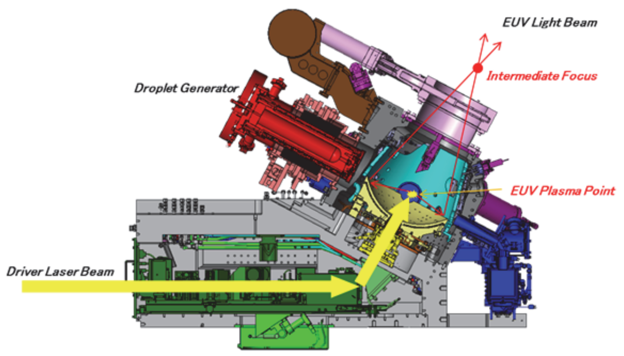

Fig. 18 Cross section of EUV chamber system

Fig. 18 is a cross-sectional view of the vacuum chamber. In the figure, the part shown in red is the droplet generator that supplies tin targets, and the part shown in blue is the droplet catcher. Tin droplets of 100 kHz and 20 μm are generated and supplied by the droplet generator, and those targets that have not been converted into plasma are collected by the droplet catcher. The structure on the yellow half hemisphere in the center is the collector mirror that collects EUV light. At the center of the mirror, a hole is opened and through which the laser bream hits the target supplied to the focal point of the collector mirror and turns it into plasma to emit light. The light emitted from the plasma is concentrated on the intermediate focus, another focus point, by the collector mirror. The generated plasma is guided toward the ion catcher by the magnetic field created by the superconducting magnet. The overall EUV chamber is positioned on the laser beam collecting unit and the chamber is mounted on the rails so that it can be drawn out from the superconducting magnet for maintenance. The chamber is entirely configured to be capable of maintaining a high vacuum state. During operation, low-pressure hydrogen gas is flowed to etch and gasify the material which could not be collected by the ion catcher and exhaust it to keep the inside clean.

5.2 Driver Laser System

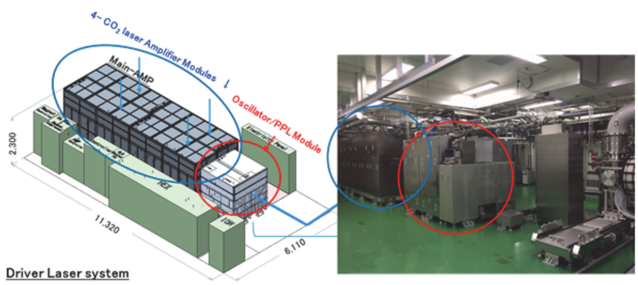

Fig. 19 Driver laser system (overall appearance)

Fig. 19 shows a perspective drawing and appearance of the driver laser system. The driver laser unit is very large, about 11 m × 6 m × 2.3 m^h including the maintenance space, but most of the space is occupied by four amplifiers for the latter stage of CO_2 laser. The CO_2-OSC section that generates pre-pulses and CO_2 seed pulses is shaped to 1.7 m × 1.7 m × 2 m. The overall configuration of the CO_2 laser amplification system is shown in **Fig. 20**. The seed pulse section is constructed using QCL lasers, the middle stage uses small CO_2 gas lasers, and the latter stage uses CO_2 lasers originally designed for industrial sheet metal processing, which enhances reliability.

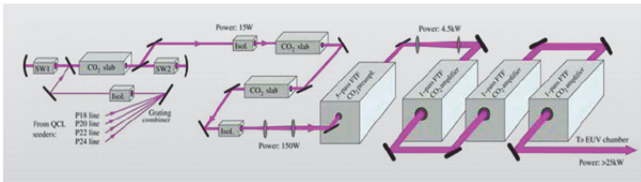

Fig. 20 Driver Laser System (CO_2 Laser)[25]

The latter stage CO_2 laser is constructed by four amplification units developed specifically for this application by Mitsubishi Electric Corporation, as explained in Section **4.**[26]. **Fig. 21** shows their external view. The size may be imagined in comparison with standing persons.

Fig. 21 External view of CO_2 laser final amplification section

5.3 Target Shooting System

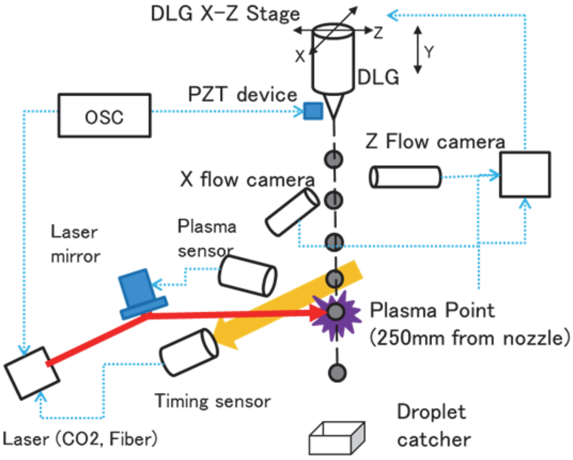

Fig. 22 Shooting system configuration

Fig. 22 shows the configuration of the shooting system for generating plasma by droplet target irradiated with lasers. The droplet generator is mounted on the X-Z stage in a vacuum chamber. The trajectory of the generated droplets are measured by flow cameras of X and Z, and the stage is controlled so that the target always passes through the same point at the virtual plasma point. In addition, the interval of the droplets is measured to accurately control the timing. By synchronizing the timing of the pulsed laser light and the focusing position of the beam with the aboves, shooting is performed accurately both in time and space. **Fig. 23** shows a photograph of the EUV light source control section operating the unit while monitoring the state in real time.

Fig. 23 External view of EUV light source control section

5.4 Latest Test Results

An example of operation data obtained by using these hardware components of Pilot #1 is shown in **Fig. 24**. In approximately 5 continuous hours of operation with EUV output of 105 W (in burst) and average output of 100 W, high duty operation (Duty = 95%), high efficiency operation (CE = 5%) and stable emission data (3σ < 0.5%) were confirmed (**Fig. 24**). The operation with high output power of 100 W level and CE = 5% is the world's highest level of driving.

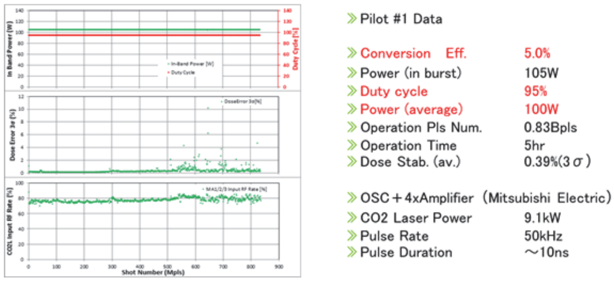

Fig. 24 Latest operation data of Pilot #1

In order to achieve an operation with CE = 5%, we have been added a number of engineering improvements based on the experiments with a small experimental unit in 2012 and that with Proto #2 from the beginning of 2016. **Fig. 25** shows the details of these improvements. The possibility of realizing CE of about 5% was suggested from the experiments of small experimental unit. Primarily, we could only achieve about 3% of CE in high-power unit. However, 4% was reached on Proto #2 by improving the pre-pulse laser and the accuracy of shooting. Furthermore, 5% CE was achieved on Pilot #1 by improving the driver laser.

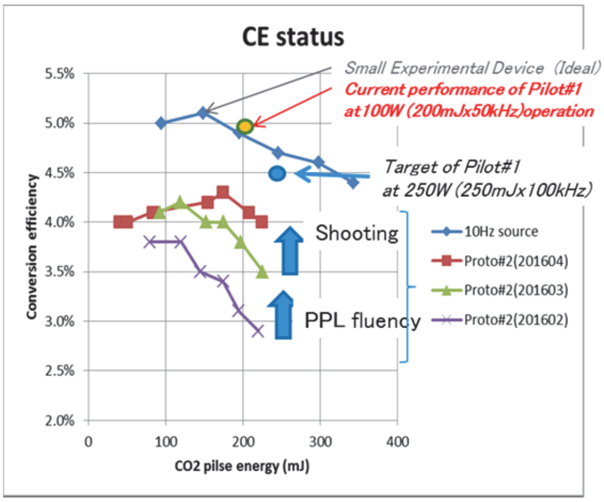

Fig. 25 Conversion efficiency of Pilot #1

We are also attempting to measure the parameters of EUV light source plasma (electron density, temperature, ion density, and temperature) directly in order to improve the accuracy of simulation, and examining the possibilities of higher efficiency based on these parameters. The progress of future research is expected[27)].

6. Conclusion

As mentioned above, EUV light source development has been led by the private-sector. Currently, the full-scale introduction of EUV lithography to semiconductor mass production fab is no longer at the stage of "if", but "when". Furthermore, regarding the performance issues of the EUV light source, not only the short-time luminance performance, but also duty, availability and running cost are also discussed. To show the current status of the EUV light source device, **Table 3** summarizes the data described in this paper in the chronological order.

Table 3 Summary of operation data and development objectives

	2016 Mar.	2016 Jun.	2016 Aug.	2016 Sep.	2016 Sep.	2016 Dec.
	Proto#2	Proto#2	Proto#2	Proto#2	Pilot#1	Pilot#1 target
Power (av.)	79-52W	128W	62-99W	101W	100W	250W
Duty Cycle	40-50%	50%	50-80%	95%	95%	100%
Power (in Burst)	158-132W	256W	115-124W	106W	105W	250W
Dose Margine	40%	15%	30-35%	30%	30%	30%
Power (open loop)	221-184W	301W	177W	151W	150W	325W
Conv. Eff. (CE)	3.5	4.0%	4.0%	3.8%	5.0%	4.5%
Operation time	119h	-	56h	49h	5h	>1000h
Rep. Rate	100kHz	100kHz	50kHz	50kHz	50kHz	100kHz
CO2 Laser Power	15kW	20kW	13kW	11.9kW	9.1kW	25 kW

On another front, development of more shorter wavelength light sources is under way by collaboration with global researchers of atomic spectroscopy and enterprises. At the EUV light source workshop held in Dublin every November, a search of multilayer film in the short wavelength region was presented, and the possibility of a multilayer film with high reflectivity in the 6.7 nm region was proposed by a European exposure tool manufacturer[28)]. Furthermore, it was presented that high efficiency emission of about 2% was confirmed experimentally by EUV emission experiment by CO_2 laser using Gd, Tb, etc.[29)], and the possibility of higher efficiency was suggested. As a recent trend, a proposal of lithography by kW-class EUV light sources using free electron laser is under investigation mainly in Europe and the United States[30)].

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