Technical paper

Development Status of High Power EUV Light Source Development for Exposure in Semiconductor Mass Production

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Gigaphoton is progressing with development aiming at mass production of 250 W (@I/F) EUV light sources for mass production plants going beyond the 10 nm node. We like to report the development status of the first generation commercial type unit. The facility was constructed in Gigaphoton Hiratsuka plant, and its operation started from September 2016. The latest data of the system test in the 1st pilot machine has demonstrated that stable emission data (3σ < 0.5%) can be obtained under Duty = 95% continuously for 134 hours in the exposure operation simulation of 113 W (in Burst) of EUV output. Currently we are continuing life tests of the collector mirror.

***Key Words**: Semiconductor manufacturing, lithography, EUV, extreme ultraviolet light, pulsed carbon dioxide laser*

1. Introduction

Despite the declining trend of the semiconductor manufacturing industry in Japan over the past decade, the demand for semiconductors worldwide has steadily expanded at an annual rate of about 4%. In the lithography process of the reduction projection exposure tool, which is the core of semiconductor microfabrication technology, KrF excimer laser is used for 180 nm and below, ArF excimer laser is used as mass production equipment for 100 nm and below, and in the advanced mass production line of 65 and below, ArF immersion lithography technology is used. For 45 nm and below, an exposure tool that realizes double patterning technology for ArF immersion lithography has been introduced in the mass production process of 32 nm and 22 nm NAND flash memories, which are currently the mainstay. For the subsequent 16 nm, EUV lithography that uses the extreme ultraviolet light (EUV) of 13.5 nm was regarded as the favorite, but from the problem of light source output, it was removed from the selection of mass production technology (2012), and now introduction of ArF liquid immersion lithography combined with multi patterning has begun. As of 2016, the market size of lithography excimer lasers is beyond 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 due to immersion are expressed by the following equations called the Rayleigh's equations. That is;

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

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

k_1, k_2: Experimental constant factor

N: Refractive index, λ: Wavelength

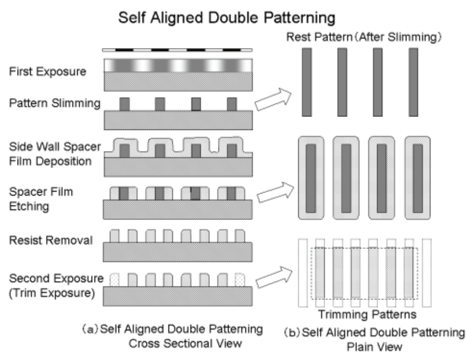

Fig. 1 Example of double patterning technology [1]

However, k_1 in this formula cannot be lowered to 0.25 or lower 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 multiple 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 (4 kHz, 0.5 pm (E95), 45 W) with unique injection lock system in 2004, Gigaphoton then released GT60A (6 kHz, 0.5 pm (E95), 60 W) in 2005, and the series has continued to evolve to GT64A with 120 W output [3] (**Fig. 2**). The "GT series" has already been used in mass production factories in large quantities and has been highly appreciated by end users for its high operation result (Availability > 99.6%), while casting a skeptical glance at EUV which has been delayed in appearance. 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 the Lehman shock. However, it recently has been highly appreciated by overseas users for its superiority of energy saving performance, and our share began to rise again. Our global market share was 52% in FY 2014, and exceeded 63% in FY 2015 (**Fig. 3**). Gigaphoton has practically grown into a light source manufacturer shipping the world's highest number of excimer lasers.

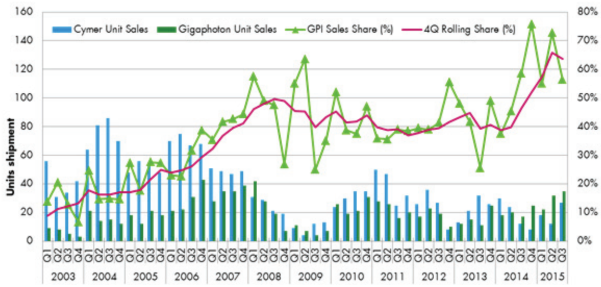

Fig. 3 Worldwide market share of excimer laser for lithography (Data source: Gigaphoton)

2. EUV Lithography

2.1 EUV Lithography and Development Background

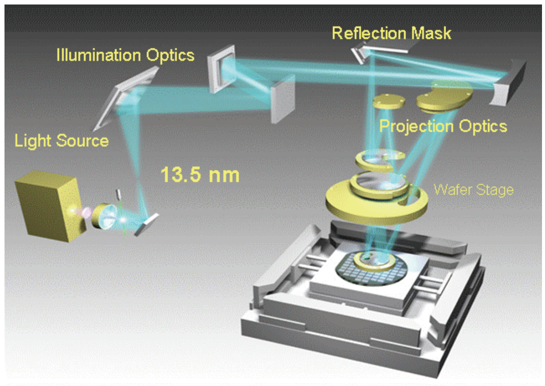

Fig. 4 Conceptual diagram of EUV lithography exposure tool

Reduction 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 a 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 a 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 a 300 mm wafer, the light source requires an output of 250 W or higher.

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

	R (K_1=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

The debut of EUV lithography is delayed because the output of light source is still the bottleneck. However, due to the magnitude of its ripple effect, a great amount of R & D expenditure is spent worldwide for this technology which is believed to be the favorite in the next generation 11 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 more is under way. Furthermore, anamorphic optics with less light loss and different longitudinal and lateral magnifications was proposed and its development is in progress. However, it is said that the next generation system will require 500 W or higher output because of the lowering 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 and an optical system with NA = 0.6 can be realized, resolution of 5 nm or less 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 exposure 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. Then, in 2006, the full-field α-Demo-Tool, which was a full-fledged exposure tool leading to current exposure tools, was developed by ASML. This exposure tool had a discharge plasma light source of 10 W class (design value) as a light source, and was 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 EXTREME's DPP light source and five equipped with Cymer's 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.

Though ASML has mounted an EUV light source of 250 W (design value) in a gamma version of EUV exposure tool NXE-3300 and attempted to achieve the productivity of 200 WPH or more [9], it has been reported that the light source has been initially operated at the level of 10 W in multiple ASML user sites and then operated at the improved level of 40 W in the field at last in August 2014 to achieve the performance of 600 WPD (Wafer Per Day). 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. 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, EXTREME who preceded with the α-Demo-Tool was dissolved in May 2013. The light source manufacturers are literally within the turbulent "Death Valley".

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

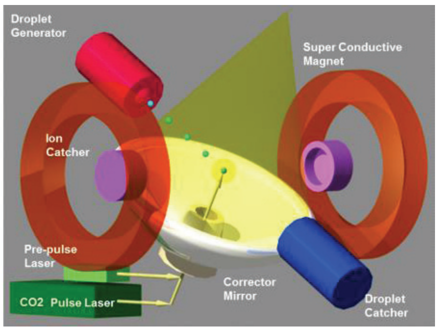

Fig. 5 Concept of EUV light source of Gigaphoton Inc.

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. One is a Discharge Produced Plasma method using pulse discharge [11], 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 [12] 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 [13]. Then, triggered by the measurement results [14] 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 favorite, 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 laser as an amplifier. This system amplifies the high repetition pulse light (100 kHz, 15 ns) of the oscillation stage by the multiple CO_2 amplifiers [15]. The target is liquid Sn droplets of about 20 µm generated by heating Sn to the melting point. The authors are addressing the stabilization of this generation technology. 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 magnetic field ion control is used 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 [16]. This result could be well explained by Nishihara et al's theoretical calculation result and the conversion efficiency [17]. Furthermore, in 2012, we optimized the pulse width of the 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 achieved with a 40 kW pulse CO_2 laser [18].

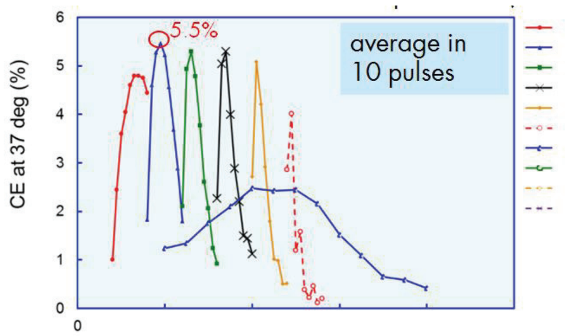

Fig. 6 EUV conversion efficiency (EUV light/CO_2 laser)

4.2 Development of High Output CO_2 Laser [19][20]

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 of 15 ns, 100 kHz was demonstrated (**Fig. 7**). Based on this achievement, this amplifier was shaped to a practical level and experiments to generate high power EUV plasma were started at Gigaphoton in spring of 2014. According to the test results, the output conventionally limited to 10 kW was improved up to 20 kW. Currently, a system in which four units of this amplifier are arranged in series is under development (5. Development of EUV Light Source System).

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

4.3 Magnetic Field Debris Mitigation [21]

Radiating carbon dioxide laser light to tin liquid droplets by radiating pre-pulse laser light, causes EUV emission. After that, tin ions guided by the magnetic field are discharged along the magnetic lines of force (**Fig. 8**).

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. Though deposition of Sn by back diffusion from the ion collector of the magnetic mirror was observed in the periphery of the collector mirror (**Fig. 9**), the result of simulation has demonstrated that debris can be significantly reduced at the position of the light collecting mirror in the EUV generation test by controlling the etching gas flow path (**Fig. 10**), and an attempt to transmit EUV light to the EUV light radiation part for three days has been completed successfully in the first prototype machine of 10 W.

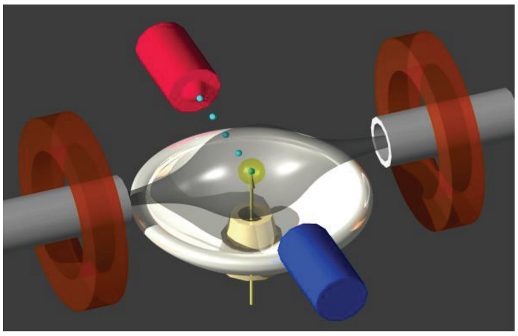

Fig. 8 Structure around the collector mirror

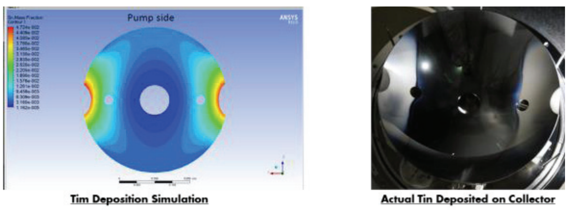

Fig. 9 Sn contamination of the EUV mirror section

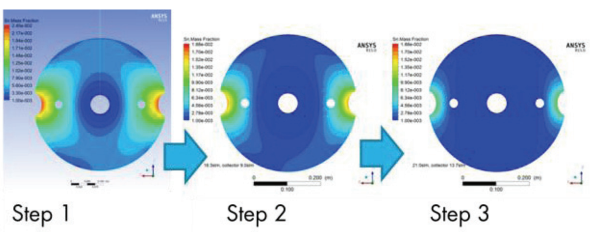

Fig. 10 Improvement of back diffusion from ion collector

In addition, the latest data (November 2015) of the system test in the prototype second machine has demonstrated that stable emission data ($3\sigma < 0.5\%$) can be obtained under Duty = 75% continuously for 143 hours in the exposure operation simulation of 113 W (in Burst) of EUV output (**Fig. 11**).

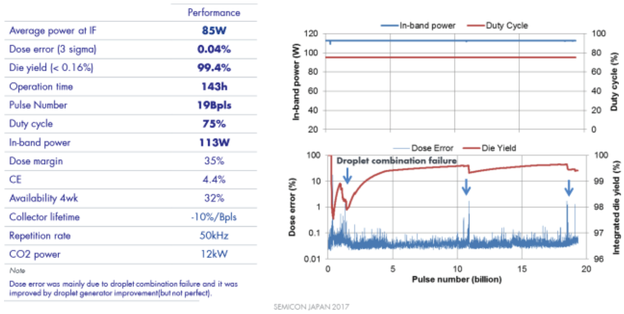

Fig. 11 Latest data of EUV light source (113 W, 143 h, Duty < 75%)

5. Development of EUV Light Source System [22]

Gigaphoton is aiming at realization and mass production of 250 W (@I/F) EUV light source for mass production plants going beyond the 12 nm node in 2017. **Fig. 12** shows an outline of the first generation commercial type unit (Gigaphoton GL200E). 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 light to generate EUV light. Gigaphoton has completed the construction of this equipment in its Hiratsuka plant (**Fig. 13**), and are now performing full-scale operation tests.

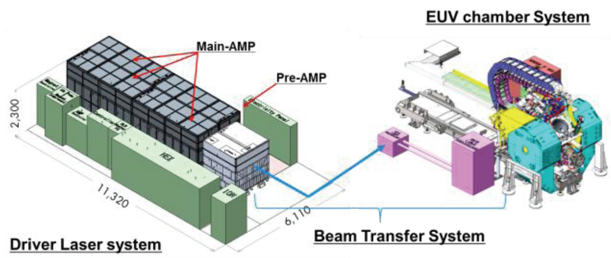

Fig. 12 250 W EUV light source GL200E-Pilot

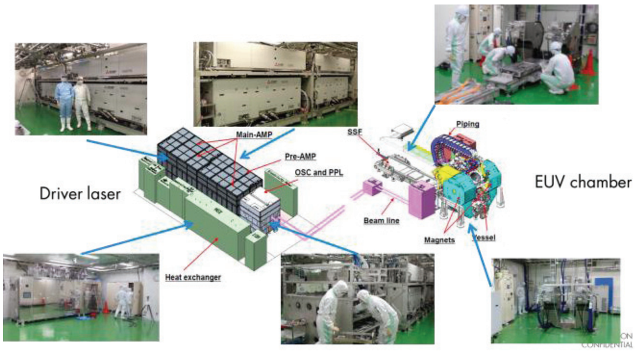

Fig. 13 Construction of pilot equipment

At present, an actual collector mirror is mounted to observe the decrease in the reflectivity with the pilot equipment. We succeeded in operating the equipment at about 100 W (in burst) for about one week with a very low drop rate of -0.4% / Billion pulse. In the future, we are planning to carry out further verification with longer operation times.

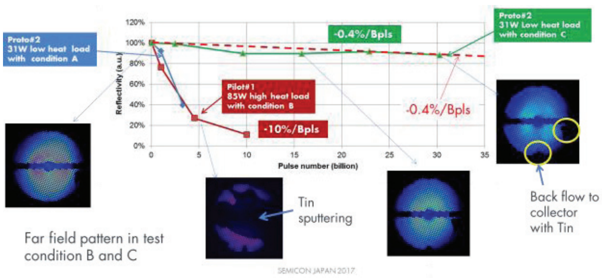

Fig. 14 Reflectivity measurement of actual corrector mirror

6. Conclusion

As described so far, EUV development has finally reached the era of international competition on a commercial basis as the result of efforts mainly made by private companies. In 2017, leading logic device manufacturers such as INTEL, Global Foundry, TSMC and Samsung Electronics declared mass production by EUV. In 2019, semiconductor mass-production lines with dozens of EUV units will be realized [23]. Besides, the EUV light source manufacturers have encountered an era in which their success or failure depends on not only the short-time luminance performance, but also long-term stability, lifetime, and availability of the components.

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[A comment from the authors]

A part of EUV light source development was done by EUVA as part of NEDO's "Research and development of fundamental technology for extreme ultraviolet (EUV) exposure system" from 2003 to 2010. The research and development of high power CO_2 laser system after 2009 was carried out with subsidies received from NEDO's "Energy Saving Innovation Technology Development Project" in FY2009 to FY2011 and in FY2011 to FY2012. Currently, research and development is being conducted in the "NEDO Program for Strategic Innovative Energy Saving Technology" as part of "Development and demonstration of High Efficiency LPP EUV Light Source" for FY2013 to 2015. We would like to express our appreciation to the organizations concerned who have been supporting the research stated here.

We also thank for the considerable efforts of employees of Gigaphoton involved in EUV light source development. At the end, we sincerely express our appreciation, in deepest sympathy, for Mr. Yoichi Tanino who worked as a key researcher in the joint development with Mitsubishi Electric Corporation and suddenly passed away in February 2014.