Technical Paper

Development of Light Sources for Lithography at Present and for the Future

Hakaru Mizoguchi

Takashi Saitoh

Takashi Matsunaga

In projection reduction photolithography processes, the heart of semiconductor mass-microfabrication, KrF excimer lasers are used for 180 nm and below, ArF excimer lasers are used for 100 nm and below, and advanced ArF immersion techniques are used for 65 nm and below. In mass-production of 32 nm and 22 nm NAND flash memories, double patterning exposure devices are used. This report describes where the development of ArF excimer lasers for lithography and that of CO_2 laser-excited LPP-EUV sources for next-generation lithography currently stand and where they are headed in the future.

Key Words: *ArF, EUV, Lithography, Production of semiconductors, Development of light sources, Pulsed CO_2 lasers*

1. Introduction

In the process of miniaturization of semiconductors, according to International Technology Roadmap for Semiconductors (ITRS)[1)], mass production of 22 nm NAND flash memories using double patterning techniques started in 2011. With regard to 16 nm technologies, the extreme ultraviolet (EUV) lithography, which had been considered the most promising solution for mass production, was nevertheless dropped for light source output reasons (in 2012) and at present, the multiple patterning (MP) with ArF immersion is being introduced. The market for excimer laser oscillators for lithography, which has been steadily growing, stood at more than 50 billion yen in 2013. Although it hasn't been appeared, EUV lithography is still considered promising, drawing huge investment in research and development across the globe, and is expected to take center stage in the next-generation 11 nm technologies and onward. This paper describes the development of ArF excimer lasers and the current and future of CO_2 laser-excited LPP-EUV sources, which is a technology originating in Japan and grabbing attention worldwide.

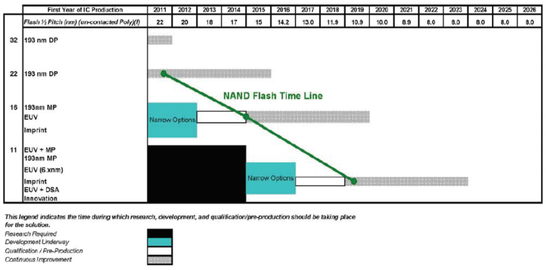


Figure LITH3B Lithography Exposure Tool Potential Solutions for NAND Flash Devices

Fig. 1 ITRS Roadmap, 2011 Edition, Lithography [1)]

2. ArF Excimer Laser Lithography

2.1 ArF lithography and immersion techniques

As indicated in ITRS[1)], introduction of ArF laser and ArF immersion exposure technology into mass production plants was under way around 2007 for a miniaturized range of 65 nm and below, and that technology has still been seeing brisk investment to date. In immersion exposure, the space between the exposure device's objective lens and the wafer is filled with liquid with a high refractive index to shorten the apparent wavelength, improve the resolution and increase the depth of focus (DOF). With immersion, resolution and the depth of focus can be expressed using the following equations.

Resolution = k1 (λ/n) / sinθ

DOF = k2 nλ / $(\sin\theta)^2$

where:

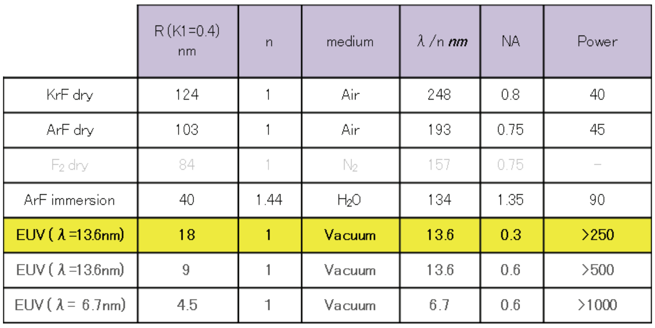
k1, k2: Experimental constant factor

n: Refractive index

λ: Wavelength

Table 1 shows the relationship between light source wavelength and refractive index.

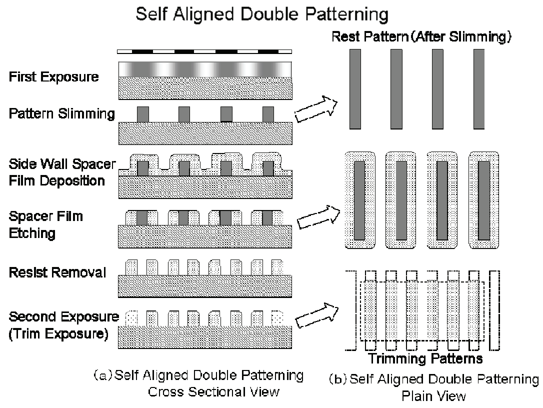
Table 1 Immersion combination of wavelength and refractive index



	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

2.2 Multiple patterning techniques[2)]

As described in 2.1, resolution can be improved by an immersion technique, i.e. by changing wavelength and refractive index. Meanwhile, it is not possible to bring k1 in the equation down to 0.25 or less with a single exposure. **Fig. 2** shows an example of basic double exposure process. As indicated in the figure, this is a technique to double the spatial frequency of the pattern that is created earlier in the initial exposure.



(a) Self Aligned Double Patterning Cross Sectional View (b) Self Aligned Double Patterning Plain View

Fig. 2 Example of double patterning process[2)]

3. Injection Lock ArF Excimer Lasers

3.1 Injection lock technology

High output and improved spectrum characteristics are key factors in improvement of lithography. A method for achieving high output, the MOPA (master oscillator power amplifier) approach is simple in design and therefore has been used for a range of lasers. This method has been used in practical lithography applications since 2002[3)].

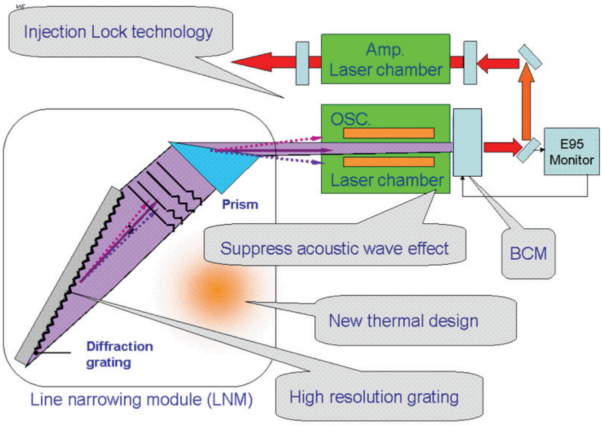


Fig. 3 Injection lock ArF excimer laser[3)]

Meanwhile, the injection lock method (**Fig. 3**), which uses a combination of two resonators, had been considered unsuitable for lithography for its high coherence. However, building upon a highly efficient and stable injection lock technique that had been developed by New Energy and Industrial Technology Development Organization (NEDO) and the Association of Super-Advanced Electronics Technologies (ASET) from their study on F_2 light source from 2000 through 2002 and upon our exclusive low-coherence resonator technique, the authors succeeded in developing an injection lock laser for practical applications[4)].

3.2 "GT Series" ArF excimer lasers

Using the injection lock laser technology developed by the authors, Gigaphoton Inc. has been mass-producing the "GT Series" light sources for ArF lithography. In 2004, the company started producing the GT40A injection lock ArF laser[5)] (4 kHz, 0.5 pm (E95), 45 W). In 2005, GT60A (6 kHz, 0.5 pm (E95), 60 W) with an oscillation frequency 1.5 times that of GT40A was launched. In 2013, GT64A with an output of 120 W was launched[6)]. **Fig. 4** shows the external view of the latest GT64A model. **Table 2** shows key specifications for GT64A. The GT40A/61A/60A/62A models have a common platform and offer high reliability and extensibility.

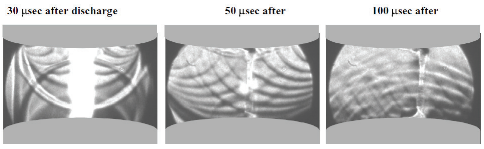
Table 2 Specifications of the GT64A

Tuning range	193.330 - 193.450 nm
Power	90 W / 120 W
Bandwidth (FWHM / E95)	0.20 pm / 0.35 pm
Repetition Rate	6000 Hz
Pulse duration	> 70 ns
Maintenance requirement	6 consumable modules
Size	2800 W × 820 D × 2050 H

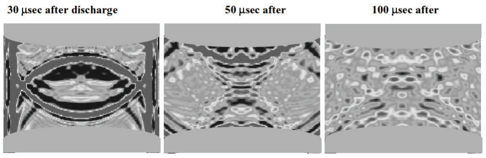
Fig. 4 External view of GT64A

3.3 Discharge technique

Excimer laser generally requires extremely quick excitation to operate. Its laser chamber is maintained at relatively high pressure, or several bar, is filled with fluorine gas, and uniform glow discharge is generated in the extended space with some ten centimeters of electrodes. In upgrading the operating frequency of the ArF excimer laser from 4 kHz to 6 kHz, comparison was made between Schlieren method-based measurements of gas density distribution in the laser discharge space and calculations made for a simulated environment (**Fig. 5**). This numerical calculations led to techniques to minimize the fluctuation of discharge caused by shock waves[7], bringing about spectrum stability in the 1 – 6 kHz range.



Figs 4. Visualized acoustic wave (measured by Schlieren method)



Figs 5. Calculated wave front (calculated by PC)

Fig. 5 Shock wave simulation and experimental data[7]

3.4 Focus drilling (FD)[8]

Because of the delay of the development of EUV, the numerical aperture (NA) of the lenses used in ArF immersion exposure is reaching its theoretical upper limit, causing the depth of focus (DOF) to reach its lower limit. In isolated, including gate, and other patternings, there has been an increase in the number of cases in which the DOF needs to be increased. Gigaphoton developed the FD system capable of instantaneously switching between the normal mode, which generates conventional narrow spectrum widths with high resolution, and the FD mode, which generates wide spectrum widths with increased DOF. This feature has been highly appreciated by semiconductor foundries, designing companies, etc. for the freedom it offers to choose between narrow and wide spectrum widths for optimum patterning in each process.

4. Development of EUV Light Sources

4.1 What is EUV lithography?

Lithography using EUV light with a wavelength of 13.5 nm is capable of reduction projection through a reflection optical system (with a reflection rate of around 68%), as proposed by Kinoshita of NTT et al[8]. Using a reflection optical system with an NA of around 0.3, resolution of 20 nm or less, which might be the ultimate limit of wavelength in optical lithography, can be achieved (**Fig. 6**). However, 13.6 nm light can be easily absorbed even by gases and therefore, any container must be filled with high vacuum or thin, high-purity gases for the light to be able to travel through. In addition, with a reflection rate being as low as 68%, reduction projection through an 11-mirror system and a large NA results in only 1.4% of the original light reaching the exposure surface. It is generally believed that a light source with an output of 250 - 1000 W would be required to achieve practical throughput.

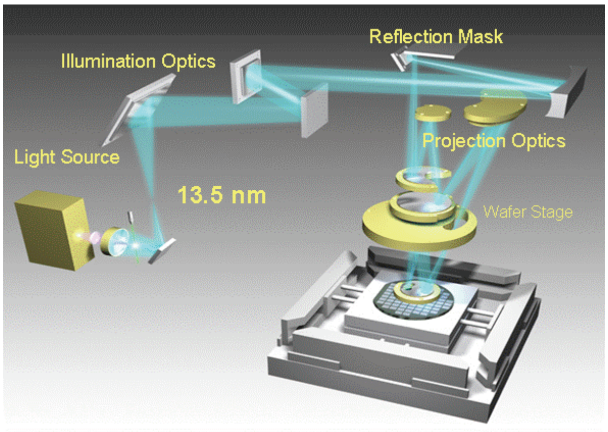


Fig. 6 Schematic of EUV exposure tool

Since 2002, Gigaphoton has been a member of the Extreme Ultraviolet Lithography System Development Association (EUVA)9). Irradiating an Sn target with a CO_2 laser is a proprietary technology of Gigaphoton. Since 2006, after reviewing the results of measurements10) by Professor Okada of Kyushu University, the company has been focusing their effort on the development of the technology. And today, the technology is the mainstream of the field. Particularly noteworthy is that optimizing the parameters of plasma induced by the double pulse method whereby YAG and CO_2 lasers are beamed at different times leads to improved conversion efficiency (>3%). This is well presented by Nishihara et al. in their theoretical calculations and conversion efficiencies11). **Fig. 7** shows a schematic of Gigaphoton's EUV source. The CO_2 laser system for plasma generation uses a MOPA system in which exclusive CW-CO_2 lasers designed for industrial applications are used as amplifiers. A maximum output of about 13 kW can be achieved by amplifying high repetition optical pulses (100 kHz, 15 ns) at the oscillation stage using multiple CO_2 amplifiers12). Sn is heated up to the melting point to obtain Sn droplets. The EUV collector mirror is positioned near the plasma to reflect and condense EUV light on the illumination optical system of the exposure device. Spattering damage caused by high-speed ions to the multilayer film over the mirror surface is reduced by controlling the ions with a unique magnetic field.

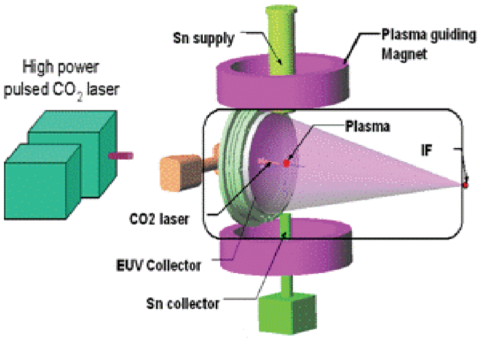


Fig. 7 Schematic of gigaphoton EUV source

4.2 Development of exposure devices across the globe and the current global market

Global competition to develop exposure devices for mass production started in 2006 when ASML's first α-Demo-Tool units were delivered to Interuniversity Microelectronics Center (IMEC) in Europe and Semiconductor Manufacturing Technology (SEMATECH)'s Albany Laboratory in the U.S13). In 2007, Nikon Corporation delivered EUV-1 unit to Semiconductor Leading Edge Technologies, Inc. (SELETE) and publicized exposure-related data. In 2009, ASML developed the full-field EUV β NXE-310014). A total of six units were shipped: one equipped with discharge-produced plasma (DPP) light source by EXTREME technologies GmbH and the remaining five units equipped with laser-produced plasma (LPP) light source by Cymer. Initially, a throughput of 100 WPH was targeted with 100 W-class EUV source. However, the output performance has remained low and stands at 7 – 10 W in 2012, a drag in the ongoing verification of EUV lithography. Currently, the full-field EUV γ NXE-3300 is being developed, which will be equipped with 250 W-class EUV light source to achieve a throughput of 200 WPH or more. The first unit is expected to be shipped out in 201315). Currently, this device uses a 40 W light source, and its data on 6-hour operation has been publicized. Plans have been publicized to upgrade the light source to 250 W by 2015. With the slow progress towards full-fledged commercialization, manufacturers of EUV light sources have been accumulating development costs, significantly squeezing their profits. Cymer was acquired by ASML to, according to ASML, help facilitate EUV development (June 2013). EXTREME was dissolved following a decision to that effect by the parent company Ushio Inc. (May 2013).

5. Improvement in Component Technologies

5.1 Improvement in conversion efficiency

In 2012, optimization of the pulse width of pre-pulse lasers led to a significant improvement of around 50% in conversion efficiency. Specifically, conversion efficiency was improved from 3.3% to 4.7% when a pulse width of around 10 ns that had previously been used was replaced with that of around 10 ps and heating with CO_2 laser pulses was employed. This is the highest level ever achieved in the world, a significant achievement (**Fig. 8**). If this level of efficiency can be obtained on final products, a pulsed CO_2 laser with an average output of 21 kW would realize an EUV output of 250 W and a 40 kW-class pulsed CO_2 laser would realize an EUV output of 500 W16).

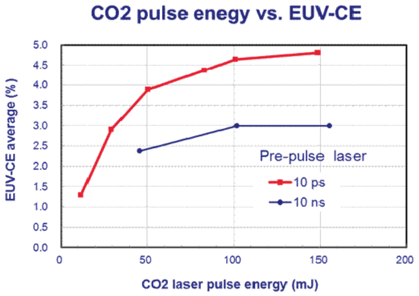


Fig. 8 EUV conversion efficiency

5.2 Magnetic mitigation

Fig. 9 shows the scheme being developed by the authors to mitigate tin debris. CO_2 laser beam absorption can be improved by adjusting the conditions for pre-pulse laser irradiation and optimizing tin shapes. In short, tin droplets are irradiated with pre-pulse laser beams and then with CO_2 laser beams to create EUV light. After that, tin ions are guided by the magnetic field and discharged along the lines of magnetic force. The latest measurements have shown that ionization efficiency can be improved to 99% or more with the combined use of 10 ps pre-pulses and CO_2 laser beams, the same combination described in 5.1.

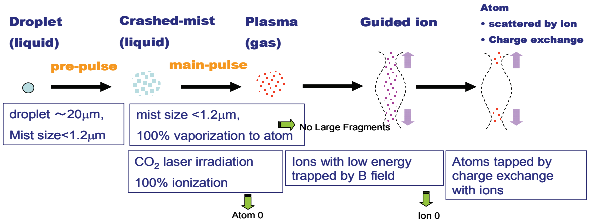


Fig. 9 Schematic of magnetic mitigation

5.3 Development of high power CO_2 lasers17) 18)

In fiscal years 2011 and 2012, with support from NEDO the authors teamed up with Mitsubishi Electric Corporation in a project aimed at achieving an EUV output of 250 W. A pulse oscillator by Gigaphoton and a four-stage amplifier by Mitsubishi Electric were combined. Using 100 kHz, 15 ns pulses, the CO_2 laser amplifier output of more than 20 kW was achieved (**Fig. 10**).

Fig. 10 Picture of high power CO_2 laser equipment

6. Development of EUV Source System16)

Currently, Gigaphoton is developing the second-generation system (GL200E). **Fig. 11** shows the external image of the system. CO_2 laser equipment for pre-pulse laser beams and main plasma heating is located on the lower floor called the sub fab. On the upper clean room floor, an EUV chamber is positioned and optically connected with an exposure device. Inside the chamber, Sn droplets are irradiated with laser beams to generate EUV light. **Fig. 12** shows the prototype. Since 2012, efforts have been made to improve related components, including major redesigning of the droplet generator, to achieve stable, high-power running of the CO_2 laser. The latest data (as of August 2013) confirmed continuous light emission with an EUV output of 15 W in the burst mode (0.5 s ON / 0.5 s OFF). Gigaphoton aims to achieve 250 W-class (@I/F) EUV sources and the mass production of these sources as early as 2015.

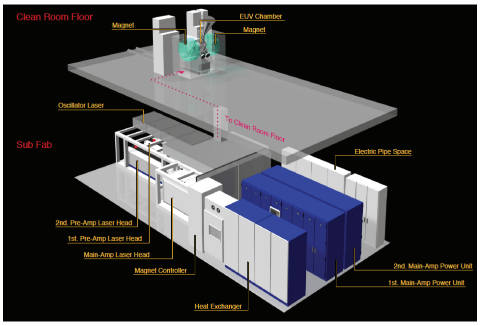


Fig. 11 General view of the GL200E EUV source

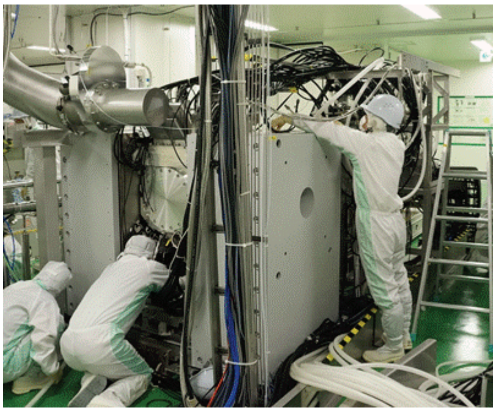


Fig. 12 Picture of the prototype GL200E EUV source

7. Conclusion

Leaving the delaying EUV system far behind, Gigaphoton's GT40A/60A/61A ArF lasers are rapidly penetrating major markets around the world buoyed by their high availability rates (>99.6%), with shipments already surpassing 1,100 units. The collapse of Lehman Brothers and subsequent financial crisis in Europe led to a declining sales trend in the Japanese semiconductor industry and, with that, the company's sales slumped. However, Gigaphoton soon started to turn its performance around, helped by the fruits it has been reaping from its new laser technology development programs (**Fig. 13**).

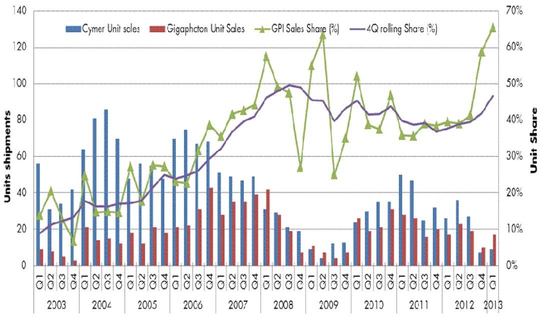


Fig. 13 Worldwide sales of excimer lasers for lithography (Source: Gigaphoton)

The development of EUV has entered into a new phase of competition being fought largely by private enterprises from around the world for commercial applications. Atomic spectroscopy researchers around the world are endeavoring to develop and utilize even shorter wavelength light sources for future lithography. In the EUV Source Workshop annually held in Dublin, it is recently presented that highly efficient light emission of around 2% in EUV experiment on CO_2 lasers using Gd, Tb and other elements[9] and related simulations also indicated the possibility of even higher efficiency. Efforts are also being made on multi-layer films for even shorter wavelengths applications and a manufacturer of exposure devices in Europe suggested the possibility of multi-layer films with high reflection rates in 6.7 nm range[20]. It is hoped that basic research in this field makes further advances.

8. Acknowledgements

The development of the high power ArF excimer laser for practical applications was achieved under the "Development of F_2 Laser Lithography Technology" program, a METI (Ministry of Economy, Trade and Industry) supplementary budget project for FY1999, granted to us as a member of the Association of Super-Advanced Electronics Technologies (ASET). The commercialization of the GT40A/60A ArF excimer lasers was made possible through a FY 2002 grant program called the "Research and Development Project for Practical Applications of High Output Lasers for High Throughput Exposure Equipment," run by NEDO. Part of the EUV source development was carried out by EUVA from 2003 through 2010 as part of the "R&D Project of Basic Technology for EUV Exposure System." The development of the high power CO_2 laser system from 2009 onward was supported by FY2009 – 2011 and FY2011 – 2012 grants under NEDO's "Innovative Energy-Saving Technology Development Project." We would like to express our appreciation again for these support.

9. References

1) International Technology Roadmap for Semiconductors, 2011 Edition, Lithography (translated by JEITA) Page 23, Figure LITH3B
2) Shinji Okazaki: "Technical Trend in Advanced Lithography," Clean Technology, No.3, Vol.19 (2009), 1-6
3) H.Mizoguchi: Optical Microlithography XIX, Proceedings of SPIE Vol. #6154 (2006) [6154-78]
4) O. Wakabayashi, T. Ariga, T. Kumazaki et.al,: Optical Microlithography XVII, SPIE Vol.5377 (2004) [5377-187]
5) H. Mizoguchi, T. Inoue, J. Fujimoto, et.al,: Optical Microlithography XVIII, Proceedings of SPIE Vol. #5754 (2005) [5754-74]
6) T. Asayama, Y. Sasaki, A. Kurosu, et.al.: Optical Microlithography XXVI, Proceedings of SPIE Vol.8683 (2013) [8683-51]
7) T. Hori, T. Yabu, T. Watanabe, et.al.: Optical Microlithography XVIII, SPIE 5754 (2005) 1285-1292
8) H. Kinoshita et al., J.Vac.Sci.Technol.B7, 1648 (1989).
9) Akira Endo: "Development of EUV Lithography System," The Review of Laser Engineering vol.32 No.12 (2004) 757-762
10) H. Tanaka et. al.: Appl. Phys. Lett. Vol.87 (2005) 041503
11) K. Nishihara et. al.: Phys. Plasmas 15 (2008) 056708
12) A. Endo, the authors (11) et al.: Proc. SPIE 6703 (2007), 670309
13) J. Zimmerman, H. Meiling, H. Meijer, et.al:"ASML EUV Alpha Demo Tool Development and Status" SEMATECH Litho Forum (May 23, 2006)
14) J. Stoeldraijer, D. Ockwell, C. Wagner: "EUVL into production – Update on ASML' s NXE platform" 2009 EUVL Symposium, Prague (2009) CD
15) R. Peeters, S. Lok, E.V. Alphen, et.al.: "ASML's NXE platform performance and volume Introduction" Extreme Ultraviolet (EUV) Lithography IV, Proc. SPIE 8679 (2013) [8679-50]
16) H. Mizoguchi, "High CE technology EUV source for HVM" Extreme Ultraviolet (EUV) Lithography IV, Proc. SPIE 8679 (2013) [8679-9]
17) Y. Tanino, J. Nishimae, T. Yamamoto, et.al.: "A Driver CO_2 Laser Using Transverse-flow CO_2 Laser

Amplifiers" Symposium on EUV lithography (2013.10.6-10.10, Toyama, Japan)

18) K. M. Nowak, Y. Kawasuji, T. Ohta1 et al.: "EUV driver CO_2 laser system using multi-line nano-second pulse high-stability master oscillator for Gigaphoton's EUV LPP system" Symposium on EUV lithography (2013.10.6 - 10.10, Toyama, Japan)

19) T. Otsuka, D. Kilbane, J. White, et.al.: "Rare-earth plasma extreme ultraviolet sources at 6.5 nm", Appl. Physics Letters 97 (2010) 111503

19) K. Koshelev: "Experimental study of laser produced gadorinium plasma emitting at 6.7 nm", International workshop on EUV sources (Nov. 13-15, 2010 Doublin. Ireland) CD

20) V. Banine, A. Yakunin, D. Tuerke, U. Dinger: "Opportunity to extend EUV lithography to a shorter wavelength", Symposium on EUV lithography (2012.9.30 - 10.4, Brussels, Belgium) CD

Introduction of the writers

Hakaru Mizoguchi

Joined Komatsu Ltd. in 1982.

Joined Gigaphoton Inc. in 2000 (the year of company establishment).

Currently the Vice President & CTO

Takashi Saitoh

Joined Gigaphoton Inc. in 2000.

Currently the executive and the manager of the EUV development Dept.

Takashi Matsunaga

Joined Komatsu Ltd. in 1985.

Joined Gigaphoton Inc. in 2000.

Currently the manager of the Laser development Dept.

[A few words from writers]

Electronic gadgets have been evolving rapidly and extensively from personal computers to smart phones and tablet computers while the hub of the electronics industry has shifted from Japan to East Asia in the past ten years.

Following this trend, Gigaphoton has been expanding its operations across the globe. EUV is called the ultimate light for miniaturization.

As we move on into the era of EUV, I will continue working hard at Komatsu Shonan Plant hoping to make contributions to further advancement of the global electronics industry.