Guest Forum

The Current Status and Technical Issues, and Future Prospect for Extreme Ultraviolet Lithography

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Extreme ultraviolet lithography (EUVL) technology is to be used in 2019 as semiconductor mass production technology with line width of 16 nm circuit. I will introduce the current state, issues and future prospect for this technology development. Today, EUV technical issues as for the mass production technology are EUV light source development, EUV resist development, EUV mask development. We will introduce these technologies and discuss in detail how nanofabrication progresses in the future.

Introduction

According to the World Semiconductor Market Statistics, as shown in **Figure 1**, in 2017 it is $ 422.2 billion, the market grows by about 21.6% compared with 2016, and in 2020 it is nearing 450 billion dollars. The semiconductor market is supported by the progress of the IT industry and recent Internet to Things (IoT). This progress is largely due to the micro processing unit (MPU) and the memory by Ultra High Integrated Circuit (ULSI), and the advanced technology of ULSI is supported by semiconductor fine processing technology. According to the International Technology Roadmap for Semiconductor (ITRS) which SEMATECH centered by the Moore's Law, ULSI technologies such as MPU, DRAM (Dynamic-Random-Access Memory), NAND flash memory, etc. have been developed. Today, instead of this ITRS, International Roadmap for Devices and Systems (IRDS) which is a new semiconductor international roadmap which is centered by IEEE has been proposed. The proposals have been made on the IRDS road map towards the upstream side of the manufacturing process including lithography from the downstream side.

In the semiconductor microfabrication technology, a method of reducing the original pattern width on a mask which is a circuit pattern of ULSI is formed to a photo resist formed on a silicon wafer by a reduction optical exposure system is the mainstream technique. In this method, the minimum dimension of a pattern transferred to a lens is expressed by the Rayleigh's equation ($R=k_1\lambda/NA$), and the patterning minimum size R is proportional to the exposure wavelength λ, and is inversely proportional to the numerical aperture NA of the reduction exposure optical system, and the proportionality constant is the process constant k_1. Thus, in the proceedings of the microfabrication techniques, the exposure wavelength has been shortened and the numerical aperture of the reduction exposure optical system has expanded. We have tried to prolong the life of the photolithography by decreasing the process constant by employing the enhanced resolution technology such as a phase shift mask technology and modified annular illumination system. In this case, the exposure light source of the lithography employs a *g*-line at the wavelength of 438 nm, an i-line at 365 nm, a KrF excimer laser at 248 nm, and an ArF excimer laser at 193 nm. In addition, ArF liquid immersion lithography was used for the pattern formation of half pitch (hp) 40 nm, because

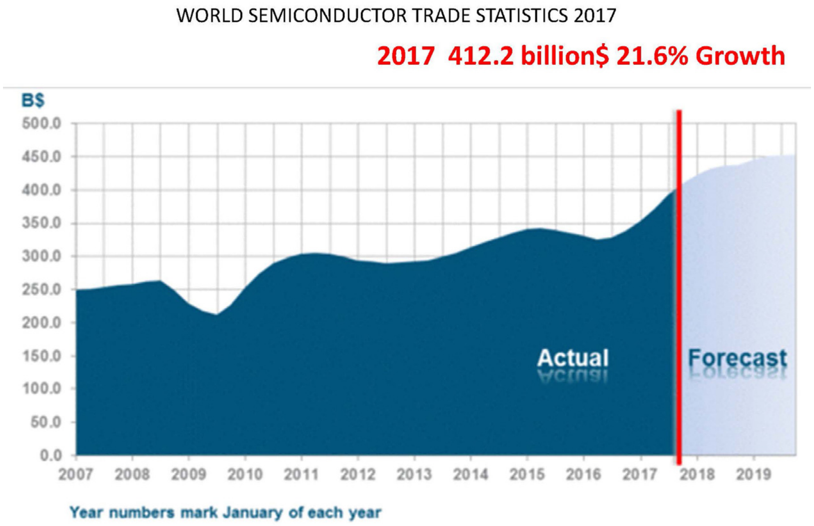


Figure 1 World Semiconductor Trade Statistics (https://www.wsts.org/)

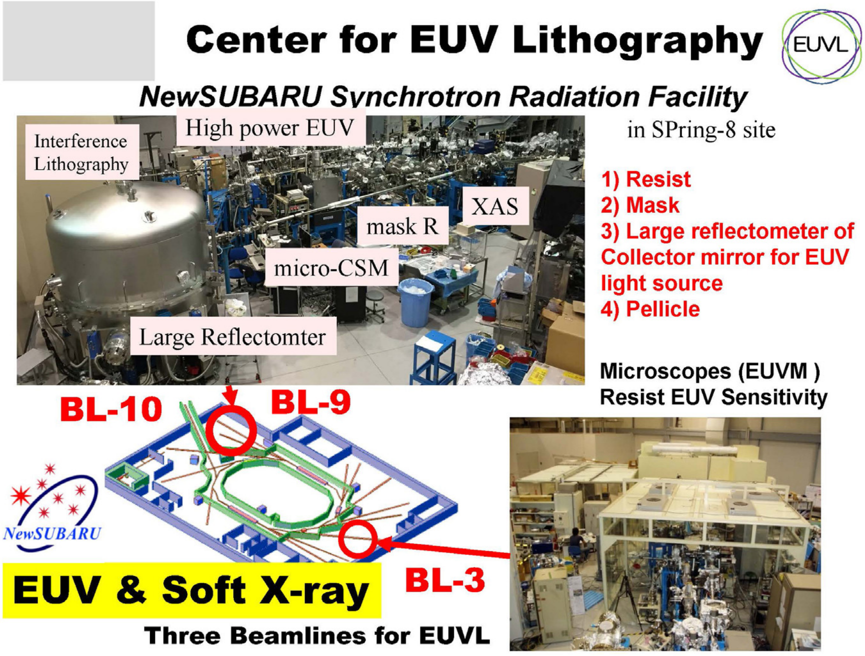


Figure 2 Beamline groups for EUV lithography at NewSUBARU synchrotron light facility

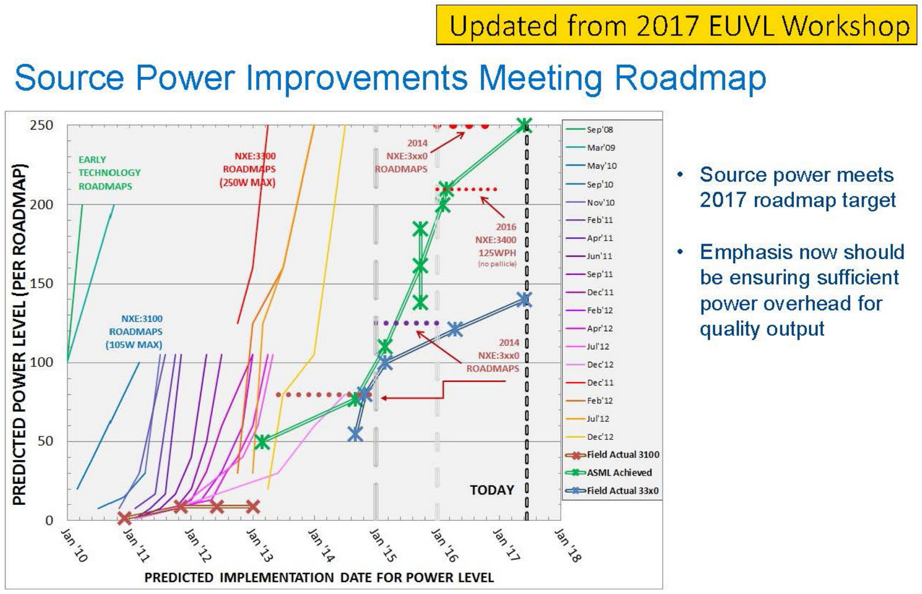
it was difficult to realize in conventional lithography. In general, the numerical aperture *NA* of the reduction exposure optical system is expressed by $NA=n\ \sin\theta$, where n and θ are the effective systems of the refractive index of the material and the lens incident angle on the optical axis, respectively. In the liquid immersion exposure system, the refractive index of pure water (n = 1.44), which is lager than that of air (refractive index 1.00), is used between the lens of the semiconductor exposure tool and the silicon wafer, Since the numerical aperture can be made larger than 1 by using it, a pattern width of 40 nm can be formed.

After that, a pattern width of 40 nm or less is required, and a multiple exposure technique based on ArF liquid immersion lithography was proposed. Since this method uses film deposition, dry-etching, and lithographic technologies, it is possible to form a finer pattern by the number of times of multiple exposure, which leads to the complexity of the process, and the manufacturing cost has become an issue.

Therefore, Extreme Ultraviolet Lithography (EUVL) technology, which can form a pattern 16 nm and beyond in a simple and inexpensive single-layered resist process, is expected to be the next generation semiconductor microfabrication technology for high volume manufacturing (HVM). And it will be used as a semiconductor production technology from 2019 by several device companies.

The Laboratory of Advanced Science and Technology for Industry, University of Hyogo has synchrotron light facility called “NewSUBARU”, and it is the largest facility in the synchrotron light facilities owned by a university in Japan, and since it began operation in 2000. Extreme ultraviolet lithography[1] research and development has been advanced at NewSUBARU since 1998. As shown in **Figure 2**, three beam lines BL03, BL09 and BL10 are beam lines dedicated to the development of EUV lithography technology, and many kinds of only-one devices are developed and installed in these beam lines. In particular, it promotes industrial support through collaborative research and commissioned research between the companies. In the research of EUV resist, evaluation of the resist resolution in large area[2, 3], pattern formation / evaluation of 10 nm pattern width by EUV interference exposure system[4], resist outgassing evaluation[5-8], development of new EUV resist materials[9-11], reaction analysis of EUV resist by soft X-ray absorption spectroscopy[12, 13], and resist permeability measurement system[14]. In the EUV mask research, we have been developing the bright field EUV microscope[15] and EUV coherent scatterometry microscope (CSM)[16, 17] for the mask defect inspection. Furthermore, for the purpose of improving the power of the EUV light source in the LPP type, large size refelctometer for the evaluation of reflectance[18] of a large-collector mirror for EUV light source were newly developed. We are developing the only-one devices as described above and contributing to the development of EUV lithography technology broadly by opening these devices to external users.

According to the IRDS roadmap, the pattern formation of 16 nm (7 nm node) is required in 2019 and pattern formation of 10 nm (5 nm node) in 2020 is required. At the 55th Design Automation Conference (DAC 2018) (held from June 24 to 28 in San Francisco, USA), an international event of electronics design, Taiwan TSMC and Samsung Electronics Corp which overwhelmed with miniaturization competition reported that EUVL will be applied to mass production in 2019. This paper


Updated from 2017 EUVL Workshop

Source Power Improvements Meeting Roadmap

- Source power meets 2017 roadmap target
- Emphasis now should be ensuring sufficient power overhead for quality output

Figure 3 Transition of achievement of LPP type EUV light source power (provided by Intel)

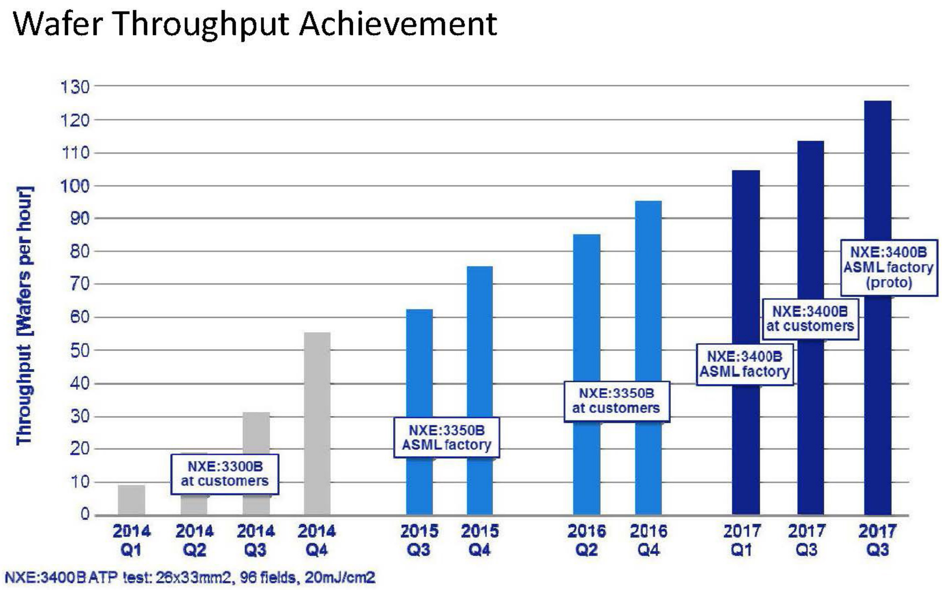


Figure 4 Changes in wafer throughput improvement of ASML's exposure apparatus

describes the current state and problem of EUVL technology development, and future development.

EUV Exposure Tool

The exposure wavelength of the light source used for EUV lithography technology is 13.5 nm. Since EUV light is absorbed by nitrogen and oxygen in the air, exposure is performed in vacuum. And compared to conventional light sources for lithography, this exposure EUV light is greatly absorbed to a substance and the refractive index of a substance is close to 1, so it is not possible to use a refractive lens system which has been used in the reduction exposure optical system of the conventional lithography technique. For this reason, a multilayer film mirror is used instead of this refractive lens system. The multilayer film is formed by alternately depositing a material having a large mass number and a material having a small mass number by a sputtering method. At this time, since the EUV light is slightly reflected at the interface at each different materials, a high reflectance can be obtained by multilayer films totally. There is a relationship of $n\lambda=2d \sin \theta$ between the light source wavelength λ, the incident angle θ with respect to the normal incidence to the multilayer film, and the film thickness d of one pair film of multilayer, which is called the Bragg's equation. Where n is the 1st order diffraction. According to this formula, when the diffraction order n = 1, when the wavelength λ=13.5 nm and the incident perpendicularly to the multilayer film ($\theta=90°$), the film thickness of one layer in the case of the Mo / Si multilayer film d is approximately equal to 6.25 nm. Considering the interference effect on the light in the multilayer film, the film thickness d is actually equal to 7 nm. At present, a multilayered film deposition technology has been established, and it is possible to obtain a reflectance of about 68% close to the theoretical value. In EUVL, this multilayered film deposition technology is applied to fabrication of exposure optical system mirror and mask substrate.

Regarding the EUV exposure tool, in the early stages of EUVL development, since the Schwarzschild optical system composed of two spherical mirrors was the mainstream in the exposure optical system, and the exposure area on the wafer was about several hundred microns, it was necessary to enlarge the exposure area for semiconductor fabrication. Therefore, NTT's research group devised an exposure optical system composed of two aspherical mirrors. By shifting the optical path of light from the center of two aspherical mirror systems, and it becomes possible to reduce the image plane distortion which has been difficult to reduce so far in the optical system of the two spherical-mirror, and it became possible to expand the exposure area. As a result, a resolution of 150 nm was confirmed in a larger exposure area. Subsequently, a research group of University of Hyogo devised a reduced exposure optical system composed of three aspheric mirrors for the purpose of realizing a resolution of 60 nm for the resist patterning, with a joint research with Hitachi Central Research and Nikon, in 1999. Successfully formed an isolated pattern with a line width of 40 nm in the exposure region of 10 mm × 2 mm. After that, through research of NEDO's re-entrustment through ASET, by improving a high thermal stability projection-optical mount system and introducing a synchronous scanning system with a mask and wafer stages, the line width of 60 nm patterning in the exposure region of 10 mm × 10 mm was demonstrated in the world first. This research result was announced at the International Workshop of EUVL held in Matsue City, Shimane Prefecture in 2001, and this research resulted in accelerating EUVL technology development, and ASML also decided to proceed with development of full-scale exposure machine after this workshop using this knowhow[2. 3].

EUV Light Source

Development of EUV light source of laser produced plasma (LPP) system is proceeding for mass production in EUVL. In this LPP method, Sn is initially excited by irradiating a Sn droplet having a diameter of 20 µm to a YAG laser, plasma is generated by irradiation with a high-intensity CO_2 laser of 25 kW, and EUV at a wavelength of 13.5 nm Light is generated. **Figure 3** shows the transition of the achievement of EUV light source power so far. In the last few years the power intensity of the EUV light source steeply improved. This is because the optimization of the size of the Sn droplet was attained and at the same time the development of a stable droplet generator advanced.

The EUV light source power required for mass production is 250 W at the intermediate focus position which is the first focus position from the light-source-generated point. **Figure 4** shows the evolution of wafer throughput improvement of ASML's exposure equipment. At present, the EUV light source mounted on ASML's exposure tool NXE:3350B is the typical light source power of 125 W at the intermediate focus position, and it is possible to expose 85 wafers of 12-inch-silicon per hour. Under such circumstances, it was reported at the SEMICON West 2017 in July 2017 that the LPP light source which has 250 W light power at the intermediate focus position developed by Cymer was succeeded to install in NXE:3400B at ASML, and the throughput of 125 12-inch-silicon wafers per hour was achieved. As a result, it is expected EUVL to be used as a mass production of logic devices from 2018 to 2019. At present, the development of EUV light source of LPP system with high power of 300 W is underway, according to Cymer and Gigaphoton, future development of light source of up to 500 W is possible with this LPP system. On the other hand, the throughput requirement for the NAND type flash memory is 200 wafers per hour, and to achieve this throughput memory suppliers requires 1 kW source power. For this light source development, a free electron laser (EUV-FEL) system for EUVL is required strongly.

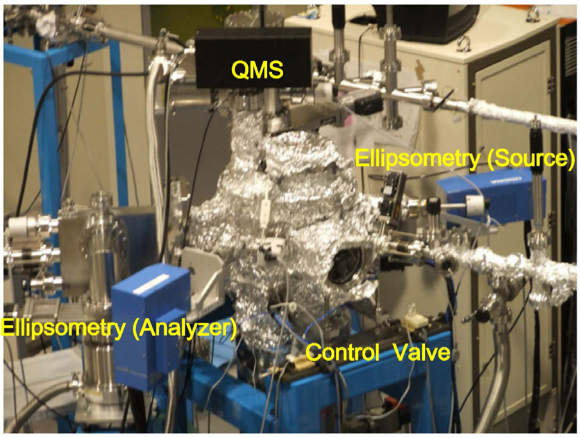
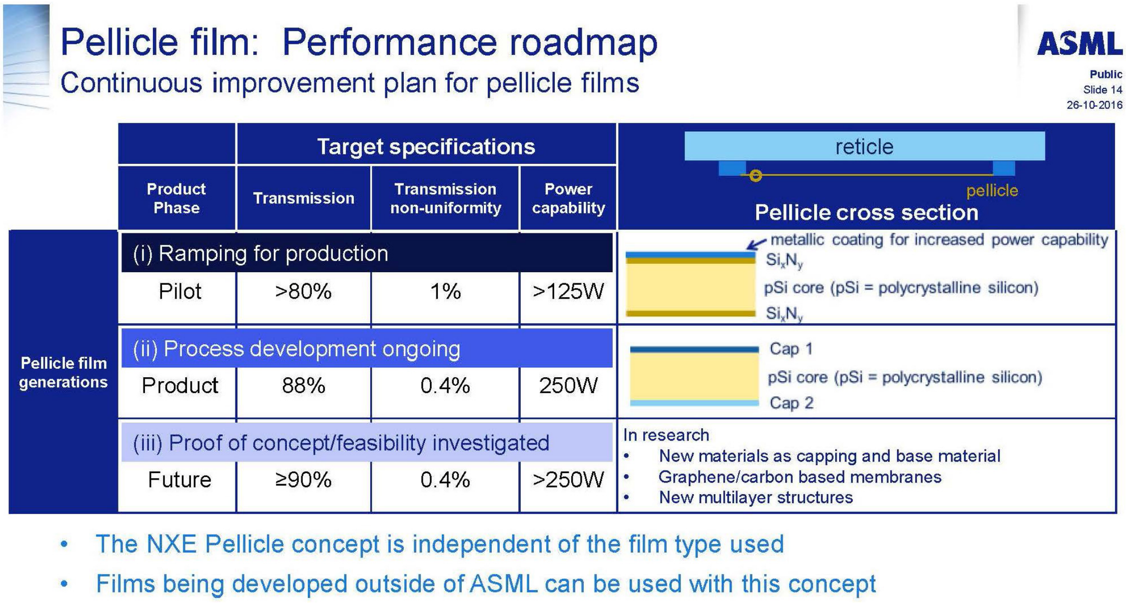


Figure 5 Resist outgassing evaluation system developed by the joint collaboration research between University of Hyogo and EIDEC

Generally, FEL consists of an electron beam linear accelerator and an undulator. Electrons generated by an electron gun are accelerated by a linear accelerator, and EUV light is generated by an undulator installed downstream. EUV-FEL which is required for mass production of semiconductors is required to develop a large current linear accelerator in 100% operation rate. Also, when used as a light source for lithography, it is necessary to convert coherent light into incoherent light. Furthermore, since more than ten exposure machines are to be installed in one FEL, if one FEL stops due to a failure, ten of the connected exposure tools stop simultaneously, which leads to a large production risk. Therefore, it is necessary to prepare a backup EUV-FEL in advance.



Pellicle film: Performance roadmap

Continuous improvement plan for pellicle films

ASML

Public

Slide 14

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		Target specifications			reticle pellicle Pellicle cross section
	Product Phase	Transmission	Transmission non-uniformity	Power capability	
Pellicle film generations	(i) Ramping for production				metallic coating for increased power capability Si_xN_y pSi core (pSi = polycrystalline silicon) Si_xN_y
	Pilot	>80%	1%	>125W	
	(ii) Process development ongoing				Cap 1 pSi core (pSi = polycrystalline silicon) Cap 2
	Product	88%	0.4%	250W	
	(iii) Proof of concept/feasibility investigated				In research • New materials as capping and base material • Graphene/carbon based membranes • New multilayer structures
	Future	≥90%	0.4%	>250W	

- The NXE Pellicle concept is independent of the film type used
- Films being developed outside of ASML can be used with this concept

Figure 6 EUV pellicle development roadmap proposed from ASML

EUV Resist Material, Processing, and Evaluation Technologies

For EUV lithography technology development required for 5 nm node which corresponds to hp 10 nm, the development of EUV resist process technology has become a top priority in the second phase of EUVL. The specification of this EUV resist is to have a resolution performance of 10 nm or less, exposure sensitivity of 15 mJ/cm^2 or less, LER of 0.1 nm, low outgasssing, simultaneously. Among them, exposure sensitivity and LER greatly influence the wafer throughput and the electrical characteristics of the device, respectively. For this reason, it is necessary for the EUV resist to satisfy high sensitivity and low LER simultaneously. Among them, realization of low LER has the highest priority, and in order to realize low LER, it is necessary to minimize the variation which called “stochastic” in reaction due to EUV light of the EUV resist to the utmost.

As described above, ASML is developing the EUVL mass production exposure tool. On the other hand, development of an EUV interference exposure tool for evaluating the resolution performance of the resist itself is underway at both of the Paul Scherrer Institute in Switzerland[19] and University of Hyogo in Japan[4]. Since the resist pattern is formed by using the transmission type diffraction grating in this exposure method, there is no need to use an optical system or a mask, and since it is not affected by aberrations of the optical system and flare and mask errors, the resist-resolution performance of the resist itself can be evaluated without any other errors.

Generally, resist is classified into chemically amplified resist (CAR) and non-CAR. Further, each type of the resists can be classified into high molecular type and low molecular type resist[11].

With JSR's conventional polymer chemically amplified resist, resolution of 13 nm can now be realized by ASML EUV exposure tool, but it satisfies both conditions of LER of 3 nm or less with high sensitivity of 15 mJ/cm^2 or less has not been reached. In addition, in the negative tone development (NTD) process of Fuji film, pattern collapse has been improved. Furthermore, Nissan Chemical Industries' Dry development rinse process (DDRP) has reduced pattern collapse, has high aspect, and improved resolution performance. Among the low molecular type resists, nanoparticle type resists are about 2 to 3 nm in size, and they are smaller by about one digit than polymer type resists. For this reason, since there is no molecular weight distribution like a polymer type resist, it is inevitably expected that there will be no variation in the chemical structure, and development is proceeding. However, there still remains issues of sensitivity, LER, outgassing, and the process stability.

Also, the research group of University of Hyogo has proposed an acid generator encapsulated chemically amplified resist that synthesizes an acid generator directly into a base polymer[9, 10], and the possibility of realizing low LER with EUV light ahead of the world Indicated. The LER of this resist was about 1/3 that of the conventional resist and exposure sensitivity was improved. Further progress is expected.

Furthermore, it is known that out of band (OoB) light, such as deep ultraviolet light (DUV), affects with LER, but due to quantification of OoB light influence toward lowering of LER. Therefore, the research group at University of Hyogo is developing the evaluation system which can evaluate the effect of OoB light on BL03A beamline of NewSUBARU synchrotron light facility. In addition, by using this equipment, the influence on resist as well as the reflectivity of the EUV mask due to the OoB light can be measured. This makes it possible to develop masks and resists which are not affected by OoB light.

As described above, various efforts have been made to solve the sensitivity and LER issues so far. However, the requirement specifications including other conditions have not been satisfied yet. With regard to achieve high sensitivity, reaction analysis of EUV resists using soft X-ray absorption spectroscopy[12, 13] has been advanced, and it was found by this analysis in the conventional CARs, not only ionized reaction but also excited reaction might be occurred under the EUV light exposure. And it was found that higher sensitivity can be realized by accelerating those reaction in CAR. Furthermore, it is difficult to realize LER with pattern formation of hp 10 nm or less by conventional empirical rule evaluation. Toward this LER reduction issue, the research group at University of Hyogo is also developing a new analytical instrument using Soft X-ray at NewSUBARU synchrotron light facility.

Meanwhile, metal-based resists are expected for developing highly sensitive EUV resists, but there is concern about the influence of metal contamination on the device process due to outgassing. In the results of outgassing study of the metal-based resists, the outgassing depends on the structure of the metal-based resist, and the evaluation of outgassing is currently being continued. **Figure 5** shows the resist outgas evaluation system developed by the collaboration work between the research groups at University of Hyogo and at the EUVL Infrastructure Development Center (formerly EIDEC)[8]. In general, when EUV light is irradiated on resist, outgassing is generated, and carbon is deposited mainly on the surface of multilayer film[5-8], and it is affected on exposure throughput of wafers. It is installed in this equipment which can evaluate the deposition of carbon in real time by using in-situ visible spectroscopic ellipsometer, and we have evaluated various resists using this equipment.

EUV Pellicle and EUV Mask Defect Inspection Technologies

Since EUV light is absorbed by nitrogen and oxygen in the air, exposure is performed in vacuum. And since the EUV exposure tool is mainly composed of a mask stage, a wafer stage, and an optical lens barrel, generation of particles in the exposure machine cannot be denied even in vacuum exposure. Therefore, also in EUV lithography, a pellicle is essential as with the lithography conventionally used for mass production. **Figure 6** shows the roadmap for development of ASML's EUV pellicle. The performance required for EUV pellicle is 1) transmittance of 90%, 2) to exposure lifetime of > 1 G shots. Currently, development of EUV pellicle materials such as SiN, SiC, and various organic materials are under the development in worldwide, and more future progress toward practical use is expected.

On the other hand, an EUV mask is formed by a Mo / Si multilayer film which reflects EUV light and is coated on a low expansion glass reticle substrate, and a semiconductor circuit pattern is formed on this surface by an absorber. Thus, the EUV mask has a three-dimensional structure, and the incident angle of the EUV light on the mask is set at 6 degrees.

In general, defects in the EUV mask are caused by "amplitude defects" due to lack of the absorber or multilayer film and particles on the surface of the multilayer film, or phase defects” due to disturbance of the multilayer structure by particles during the multilayer film deposition. In the conventional mask inspection technique, it is impossible to detect a phase defect, and at-wavelength defect inspection tool that can detect a phase defect is indispensable. The research group at University of Hyogo has been developing the bright field EUV microscope[15] and EUV coherent scatterometry microscope (CSM) which is a diffraction-type-EUV microscope employing coherent EUV light (EUV-CSM)[16] so far. Particularly in recent years, the micro EUV coherent scatterometry microscope development (micro-CSM) which is a diffraction-type-EUV microscope[17] employing coherent EUV light utilizing microbeam (micro-CSM) enables three-dimensional-defect inspection of natural defects on a EUV mask. In addition, we are pursuing the development of a diffraction microscope with standalone coherent EUV light employing, high harmonic gas (HHG) laser, and we are proceeding with demonstration of finer natural defect observation.

The actinic mask inspection system (AIMS) development for the EUV mask has been promoted mainly on Lasertec. Also, at Lawrence Berkeley National Laboratory (LBNL), a mask defect inspection tool called SHARP[20] was constructed.

As described above, the defect inspection technology for the EUV mask was advanced using these tools.

Conclusions

In the future, various electronic devices for IoT are required to have low cost and low power consumption, and semiconductor microfabrication is still indispensable. Among them, at 7 nm node and 5 nm node, it is announced that EUV lithography will be adopted for mass production technology of some chip makers.

For the EUV 1st phase of the 7 nm node production, the priorities of development issues were in order for light source, resist, pellicle, mask, but the EUV 2nd phase of 5 nm node production, it is in order of resist, light source, pellicle and mask.

At present, the development of EUV light source is currently at 250 W and throughput of wafer exposure can be achieved at 125 wafers per hour. For EUV resist, reduction of LER is the significant issue. Regarding EUV masks, the development of pellicles is underway and more future progress is expected. Furthermore, in the development of mask defect inspection technology, the performance confirmation of various defect inspection tools is energetically advanced in Japan, US, and Europe.

As described above, in the EUV lithography, mass-production applications of logic devices are being studied, and the basic research is being advanced to solve EUVL technical issues.

In the future of the development of semiconductor device technologies, higher density circuit integration is required, and semiconductor microfabrication technology is an essential technology. According to IRDS roadmap, the conventional microfabrication technologies are required until 2024, and after that the ultrafine processing techniques of hole pattern with the highest aspect ratio with minimum line width are required following development to three dimensional devices.

In any case, as miniaturization progresses as it is, since the leak current increases due to the quantum effect, the device system innovation with a small number of electrons from a CMOS device system with a large number of electrons is required. Meanwhile, new devices such as quantum devices are being actively developed, and in view of these device developments in future, the microfabrication technology is an indispensable technology.

Considering the development of novel devices, we believe that fine pattern formation technology will be required from the viewpoint of top-down and bottom-up quantity lithographic technology in the future.

Acknowledgments

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