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Review Article

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Development of core technologies on EUV mask and resist for sub-20-nm half pitch generation

Abstract: This paper reports on the current status for the key infrastructures of the extreme ultraviolet lithography (EUVL) for sub-20-nm half pitch (hp) generation. More specifically, the inspection technologies for EUV mask and resist-related technologies will be dedicatedly discussed. First, the actinic blank inspector is strongly required especially for sub-20-nm hp generation. The basic configuration of the prototyping tool will be presented. Second, the basic configuration of the newly developing patterned mask inspector (PMI) consisting of the projection-type optics for the electron beam (EB) will be presented. The primary challenge for the EUV resist is the concurrent improvements of resolution, line width roughness, sensitivity, and outgas. The basic performance of the EUV resist and preliminary validation of the outgas qualification for sub-20-nm hp will be presented.

Keywords: EUV; infrastructure; lithography; mask; resist.

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1 Introduction

The semiconductor industry has been still recognizing the benefit of the downscaling as one of the most effective ways to reduce the cost even for sub-20-nm era. The candidate lithography as the main driver of the downscaling strongly depends upon the sort of products and the timing, but the extreme ultraviolet lithography (EUVL) will most likely be chosen for sub-20-nm half pitch (hp) and beyond generation. The top runners of the downscaling have already installed the preproduction scanners [1] and have commenced the operation of the pilot lines to fix the production level issues. However, some of the key infrastructures still involve the fundamental issues. The source no doubt needs to reach the targeting power and stability immediately. There also remain the fundamental issues in the infrastructures of mask and resist. Several kinds of approaches in solving the issues have been taking place all over the world. First, the multilayer defects located beneath the multilayer of the EUV mask blank is one of the most embarrassing issues in realizing the EUVL because they cannot be repaired physically. The optical blank inspection system works well for the 22-nm hp generation [2, 3], but the actinic blank inspector (ABI) is strongly required especially for the sub-20-nm hp generation. KLA-Tencor is establishing an actinic system for both blank and patterned mask inspection [4]. Second, another issue concerning the EUV mask to be addressed is that the optical-based patterned mask inspectors (PMIs) no longer have sufficient sensitivity for sub-20-nm generation. Applied Materials, Inc. is establishing multicolumn electron beam (EB) inspection system [5]. Third, the development of EUV resist has steadily progressed to meet the requirement, however need to exceed the higher technological barrier especially for the sub-20-nm generation. The primary challenge is the concurrent improvements of resolution, line width roughness (LWR), and sensitivity of presently available and new resist platforms. SEMATECH/Berkeley METs have been contributing greatly to develop the advanced resist for down to around 16-nm hp structures [6, 7], and the interference lithography tool in the Paul Scherrer Institute has also been contributing to print a more aggressive feature size [8]. Additionally, the amount and the sort of outgassing from resist need to be controlled strictly to avoid the contamination of the optics of the scanner. EUV Technology Inc. has developed the resist outgas test setup as a commercially available tool [9]. CNSE/SEMATECH [10], IMEC [11], and NIST [12] have already established the resist outgas qualification lines.

This paper reports on the current status, issue, and provision for the development of core technologies on the EUV mask and resist for sub-20-nm hp generation in EUVL Infrastructure Development Center, Inc. (EIDEC). More specifically, the development of ABI and PMI, and resist-related technology development in EIDEC will be dedicatedly discussed in this paper. First, the basic configuration and specification of the prototype of the high-volume manufacturing (HVM) of ABI will be presented [13]. The Millennium Research for Advanced Information Technology (MIRAI) project had executed the proof of concept and validated the capability of full field ABI [14–16]. EIDEC has succeeded in the development of ABI for HVM. Second, the basic configuration and preliminary result of the newly developing PMI for sub-20-nm hp generation will be presented [17, 18]. The proof of concept of the PMI consisting of the projection-type optics for the EB has been executed in the previous work [19, 20], and this work has succeeded in the development. Third, the resist benchmarking using small field exposure tool (SFET) [21] and fundamental resist characterization leveraging immersion AFM [22] for sub-20-nm hp generation in EIDEC will be presented. The basic performance of the preliminary validation of the outgas qualification for sub-20-nm hp will also be presented [23].

2 Lithography prospect and technical challenge for EUVL

Downscaling of large-scale integration (LSI) continues to contribute to the progress of the IT society as described above. Therefore, technologies for downscaling, such as

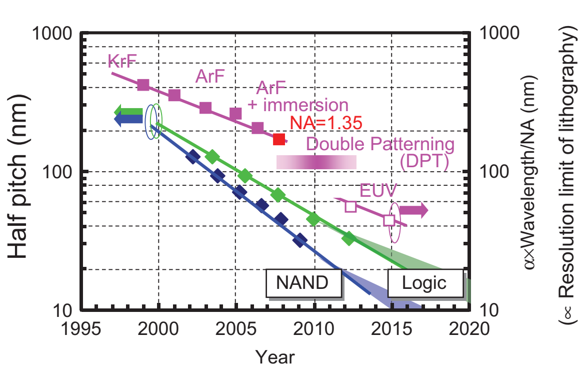


Figure 1 Trend and prospect for downscaling of LSIs and lithography to be printed.

lithography are no doubt the core element for the semiconductor industry, even for the nano-scale era. Figure 1 shows the trend and prospect for the downscaling of LSIs and lithography to be printed. The vertical axes represent the hp of the minimum feature size and the exposure wavelength divided by the numerical aperture (NA) of the projection lens of exposure tools multiplied by the coefficient, which means the resolution limit in lithography, respectively. An ArF immersion scanner with a 1.35 NA has been released in 2007, and further enlargement of the NA is not promising. Therefore, a double patterning technology (DPT) has been the realistic solution for the down to 20-nm hp technology node. EUVL will be the mainstream technology from the cost and extendibility viewpoint for sub-20-nm hp generation. EUVL will also become the main driver of miniaturization even more than the 20-nm hp for the complex pattern structures, which are relatively difficult to apply to the DPT like logic wiring structures, contact structures, and so on.

Figure 2 shows the summary of the technical challenge for EUVL. The source, no doubt, needs to reach the targeting power and stability immediately. There are two main candidate source types for HVM, which are laser-produced plasma (LPP) and laser-assisted discharge-produced plasma (LDP). However, the LPP seemed to be the mainstream for HVM from the potential reachable power point of view recently. The current power obtained in the customer's fab is, however, around 10 W at the position of intermediate focus (IF), where the targeting power for HVM to achieve 150 wafers per hour (WPH) is 250 W at the IF position. The effective debris mitigation for the collector mirror, stability of CO_2 laser, stable droplet generation, effective infrared (IR) reduction, etc. are necessary to reach the target performance. The scanner supplier has already shipped the plural number of preproduction tools to the leading device manufacturers in 2011. They have shown the preliminary performance concerning the critical dimension (CD) control and overlay (OL) control. Those were satisfactory numbers as the preliminary results, which, across wafer CD uniformity for the 27-nm feature size, was around 1.4 nm, and the OL for the single machine dedicated chuck was <1 nm (3σ) [1]. The next step will be the validation and learning to find out the defectivity and the quality level of the data correction by running the pilot production.

As for the EUV mask technology, the phase defect is one of the most serious issues as it is difficult to repair. The optical inspector makes sense for the 20-nm hp generation, but it no longer has sufficient sensitivity for the sub-20-nm generation. The ABI, which has potentially sufficient sensitivity for the sub-20-nm generation needs to be developed. However, the market size for the inspector is not sufficiently big for the equipment suppliers to incur

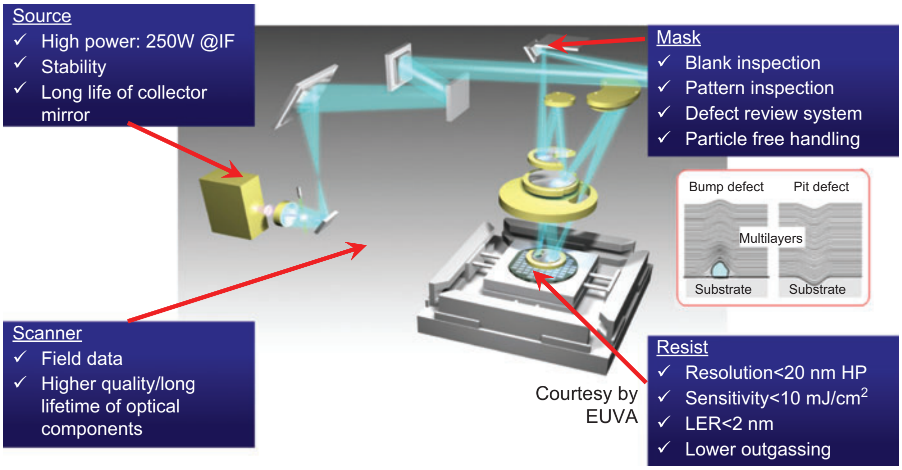


Figure 2 Summary of the technical challenge for EUVL.

the development expense. Therefore, EIDEC is collaborating with them to pursue the development as the role of the consortium in the precompetitive development field. The optical PMI does not have sufficient sensitivity for the sub-20-nm generation as described above. The actinic PMI is under development, but it will be launched onto the market in the 2014–2015 timeframe. The EB-based tools are expected to be ready prior to the actinic tools. The EIDEC is developing the EB projection-type PMI to overcome the drawback of the focused electron-based tools and obtain the desired throughput. The actinic defect review technology is inevitable not only for reviewing the patterned defect repair portion but also for reviewing the phase defect portion. The particle free handling is also inevitable because the EUV mask does not have any pellicle structures. The primary challenge for the resist technology is the concurrent improvements in the LWR, sensitivity, and outgassing as well as the resolution. Needless to say, the intensive improvement of the resist material is the first priority, but the innovative process improvement especially in reducing the LWR is significant to meet the requirements.

3 Mask-related infrastructure development

3.1 Actinic blank inspector

The development of the ABI tool was launched by the MIRAI project in 2001, and the development is succeeded by the EIDEC today as shown in Figure 3. MIRAI φ1 and φ2

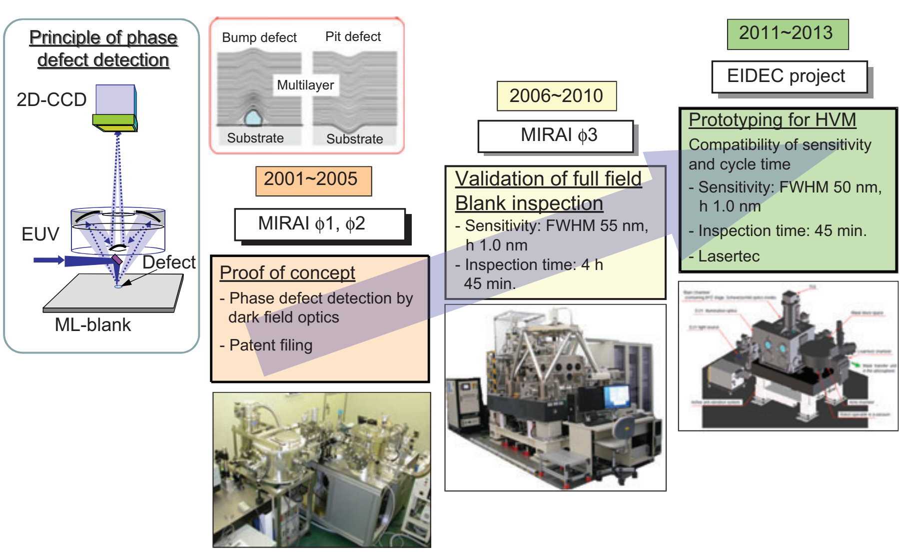


Figure 3 Development history of the ABI.

have completed the proof of concept of the ABI, which is the capability of the phase defect detection by the dark-field optics from 2001 to 2005. MIRAI φ3 has validated the full field blank inspection with the sensitivity of the full width at half maximum (FWHM) of 55 nm and height of 1.0 nm from 2006 to 2010. The inspection time was 4 h 45 min. The EIDEC is still continuing to improve its sensitivity and throughput even now. The EIDEC is now prototyping the HVM tool with Lasertec to reach the desired inspection time of 45 min with sufficient sensitivity of the FWHM of 50 nm and height of 1.0 nm as shown in Figure 4. The increase in the source power twice to four times and the transmission of the illuminator twice enables to reach the targeting inspection time [13].

Needless to say, the primary objective of the ABI is to find the smaller phase defect in improving the defectivity of the blank manufacturing process. However, it takes a long time to establish the process in achieving perfect blanks with high yield, indeed. Therefore, the industry requires the technology in identifying the precise location of the phase defects to mitigate them by shifting patterns and hiding them above the multilayer structure. The EIDEC is realizing the defect review mode in the upcoming tool having the review optics, which enables to demagnify the corresponding pixel size of the image sensor on mask dimension and to identify the position of the phase defect with higher accuracy as shown in Figure 5. The new feature having the demagnification ratio of 1/23 will enable to achieve the position accuracy of <20 nm on the mask dimension [13].

3.2 Patterned mask inspector

The minimum defect size to be detected for the EUV mask of a hp of 16-nm generation is described as 18 nm in size in the ITRS 2010 update. The EIDEC is prototyping the EB-based PMI, leveraging a projection electron microscopy (PEM) to meet with the requirements. The PEM has sufficient

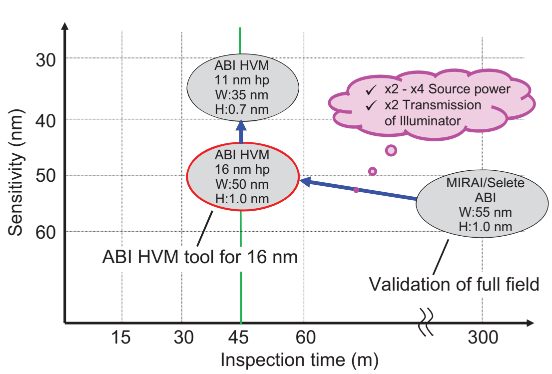


Figure 4 The progress of sensitivity and inspection time.

resolution to capture fine images of targeted defect size and structures, which the deep ultraviolet (DUV) system no longer has. It also has sufficient potential of inspection time to meet the requirement, where scanning electron microscopy (SEM) type inspection system no longer has.

Figure 6 shows the basic configuration of the electron optics of the PEM and the image processing system for the PMI. Electrons emitted from an electron gun are deflected by a beam separator and illuminate a mask surface through a cathode lens. The interacting electrons are magnified by a transfer lens and a projection lens, and are captured by the time-delay integration (TDI) sensor as the mask image. The illuminated area is wide enough to cover the sensor area. The mask stage has the function of the step and scan motion to execute a full area of mask inspection operation. The parallel image processing unit enables realization of the desired inspection time [19, 20].

The experimental PEM setup for validating the capability of the 16-nm EUV mask pattern inspection has been performed. It consisted of LaB_6 as the electron gun and CCD with a 20-nm pixel size as the image sensor. The irradiation area was 100 μm×50 μm, and the landing energy was 0–3000 eV. The mask for the test consisted of tantalum boron-nitride (TaBN), 51-nm thick, as the opaque film, chromium nitride (CrN), 10-nm thick, as the buffer layer on the silicon capping layer, 11-nm thick, and the Mo/Si multilayer with 40 pairs. Figure 7 shows the preliminary test result for the signal-to-noise ratio (SNR) of the defect detection by the experimental setup. The vertical and horizontal axes represent the SNR of the captured image and the defect size, respectively. SNR=1 indicates that the defect can be detected with a sufficient capture rate. It is found that the defect of the edge extension mode, down to 24 nm, can be identified and that of the edge intrusion mode, down to 31 nm, can be identified successfully. Further improvement is necessary for reaching the targeted number, but the system is found to be feasible [17].

4 Resist-related infrastructure development

The primary challenge in realizing the EUV resist is the concurrent improvements of the resolution, the LWR, and sensitivity. Additionally, the amount and the sort of outgassing from the resist need to be controlled strictly to avoid the contamination of the optics of the scanner as shown in Figure 8. The EIDEC has prepared the infrastructures, i.e., the small field exposure tool (SFET) and the resist outgas test setup, for developing the EUV resist to meet the requirements. The

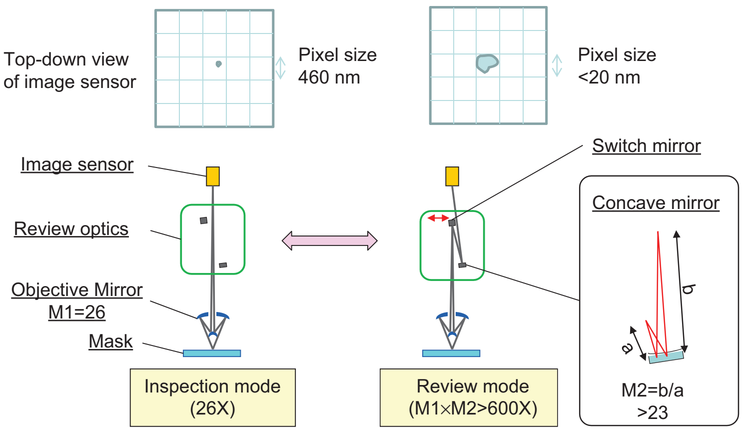


Figure 5 Schematic illustration for review optics of the ABI.

basic constitution of these infrastructures and the related outcome are elaborated in this section.

4.1 Resist development

The SFET has been fabricated by Canon [24, 25] and installed in the super cleanroom of the National Institute of Advanced Industrial Science and Technology (AIST) in order for the Semiconductor Leading Edge Technologies Inc. (Selete) to develop the 32- to 22-nm EUV resist at first [26–29]. It has 0.3 NA, 0.2 mm×0.6 mm field size, and $^1/_5$ demagnification. The EIDEC has succeeded in the basic role of Selete concerning the precompetitive resist development. The current targeting resist performance is the resolution of <20 nm hp, sensitivity of <10 mJ/cm^2, and LWR of <2 nm shown in Figure 9. The EIDEC has validated the printability of 16 nm lines and spaces (L/S) as the ultimate resolution with aggressive dipole illumination shown in Figure 10A [21]. The experimental result was consistent with the image contrast analysis shown in Figure 10B [30].

Another infrastructure in investigating the fundamental phenomenon of resist development behavior is the immersion-type high-speed atomic force microscope (HS-AFM). It can monitor the behavior of *in situ* dissolution and rinse and so on. It enables the *in situ* analysis of resist dissolution and rinse processes with high speed. Figure 11 shows the HS-AFM analysis system. Figure 11A shows a picture of the HS-AFM system (Nano Live Vision by Research Institute of Biomolecule Metrology). Figure 11B shows a detailed description of the HS-AFM, which is composed of a 'sample assembly' where the wafer sample is attached and a 'cantilever assembly' where the cantilever and developer solution (in this case, tetramethylammonium hydroxide or TMAH) is set.

Figure 12 shows the procedure utilized for *in situ* dissolution analysis. First, the designated volume of the deionized (D.I.) water is injected onto the cantilever assembly after the assembly and setup of the 'cantilever assembly' and 'sample assembly' in Figure 12A. Second, high-speed scanning is performed in the D.I. water as shown in Figure 12B. It yields the resist film state before development. Third, the designated volume of the

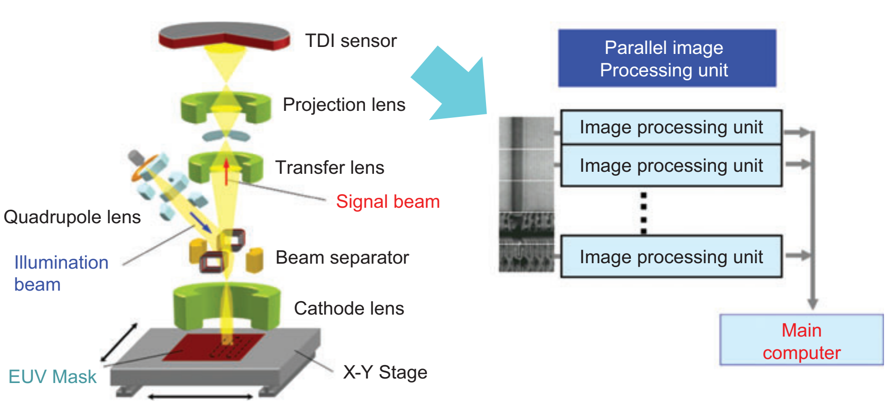


Figure 6 Basic configuration of the electron optics of the PEM and the parallel image processing system for the PMI.

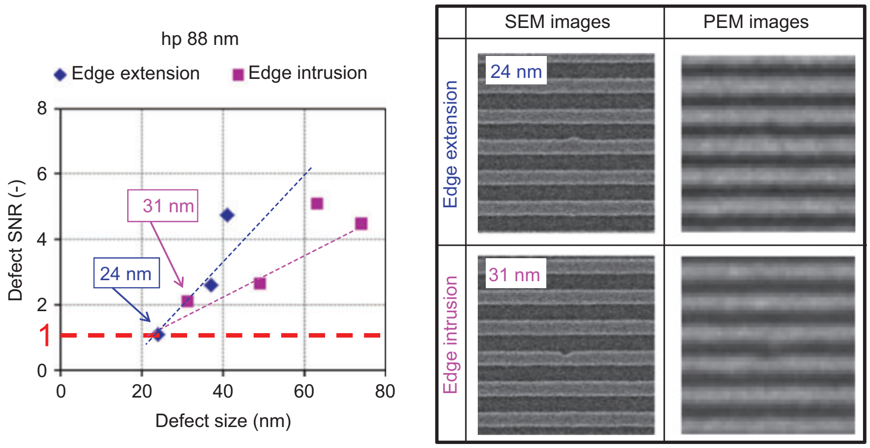


Figure 7 Preliminary test result for the SNR of the defect detection by the experimental setup.

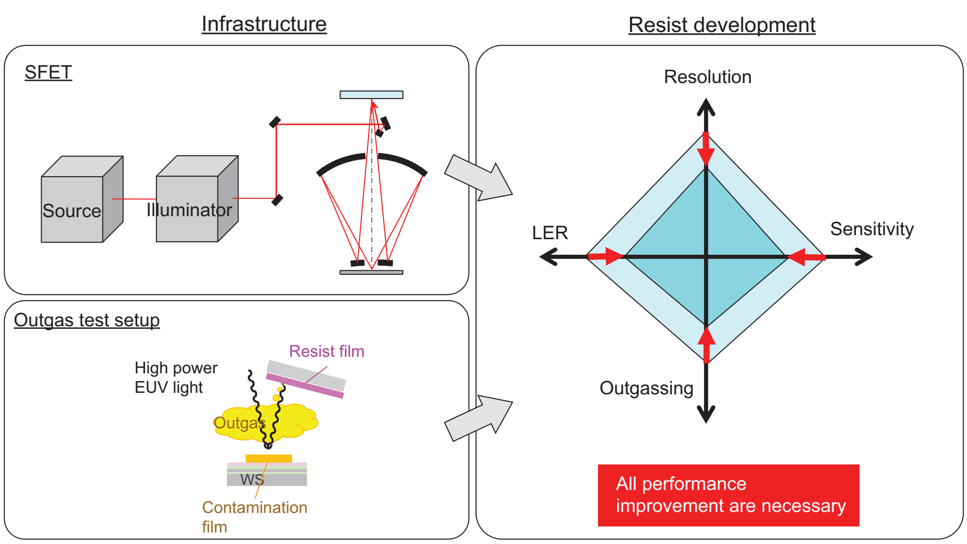
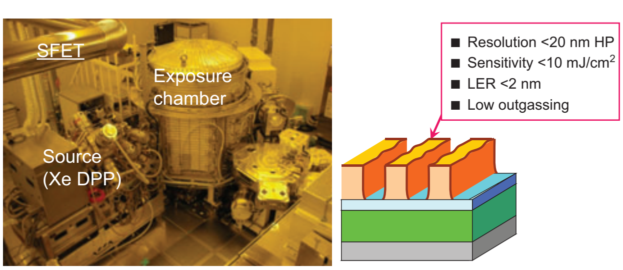


Figure 8 Metrics for the EUV resist attribute and their infrastructures for the development.

developer solution is injected, and the scanning is continued until the resist dissolution is completed as shown in Figure 12C. Finally, the developer is replaced with the rinse solution through a coordinated inject-and-dispense setup attached to the liquid puddle in the cantilever assembly in Figure 12D.

Figure 13 shows the *in situ* dissolution analysis results obtained for photo acid generator (PAG)-blended, PAG-cation bound, and PAG-anion bound acryl-based resists as the demonstration of this method. The degree of swelling during the development could be observed clearly by the HS-AFM [22]. The results indicated the extendibility of the HS-AFM to explore the behavior during the development process.



Items	Spec
NA	0.3
Field size: mm	0.2×0.6
Magnification	1/5
Source power	0.5 W @IF

Figure 9 SFET and basic specification.

4.2 Resist outgassing qualification

Outgassing from the EUV resist has been recognized as one of the most serious issues in HVM of the EUVL as

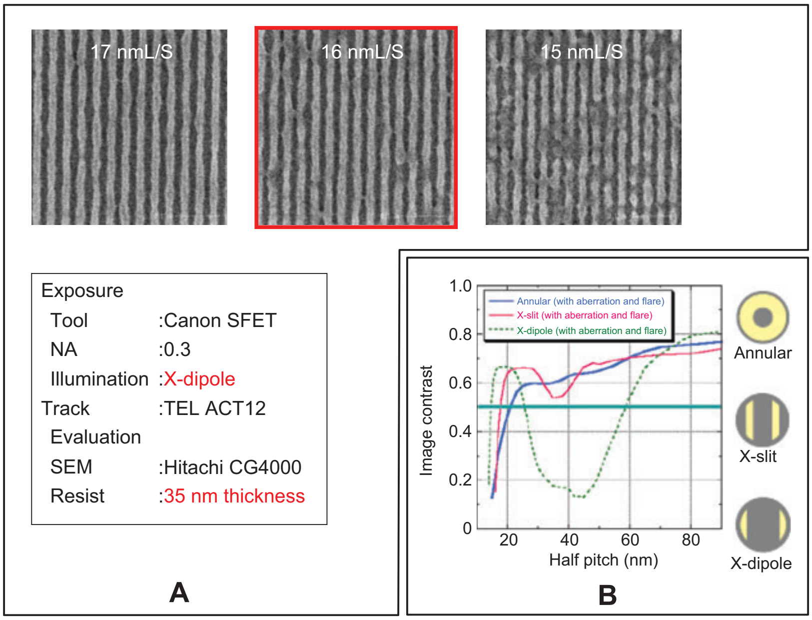


Figure 10 Ultimate resolution of SFET utilizing x-pole illumination; (A) experimental result, (B) simulation on image contrast analysis.

it results in contamination of the optics. Therefore, the industry strongly required to clarify the standard qualification protocol and the criteria of the outgassing. ASML has proposed the resist outgas qualification protocol utilizing a witness sample (WS) of the contamination film as shown in Figure 14. First, the contamination layer growth on the WS is performed by irradiating either the EUV light or EB on both WS and resist layer on the wafer. The exposure doses for the contamination test are determined by multistep flood exposure test beforehand. Second, the thickness of the contamination layer is measured by spectroscopic ellipsometer (SE). Third, the cleaning of the contamination layer on the WS is performed by hydrogen radical. Finally, the noncleanable species are identified by X-ray photoelectron spectroscopy (XPS). ASML has recommended the usage of the EB as the EB enables to accelerate the test compared to the EUV light. However, the consensus that the correlation between the EUV and the EB was not sufficient for the resist suppliers to be the official resist qualification protocol has been built up among them. Therefore, the reliable resist outgas qualification protocol and the criteria based upon the plenty of correlation data between the EUV and the EB are extremely crucial for the realization of the EUVL.

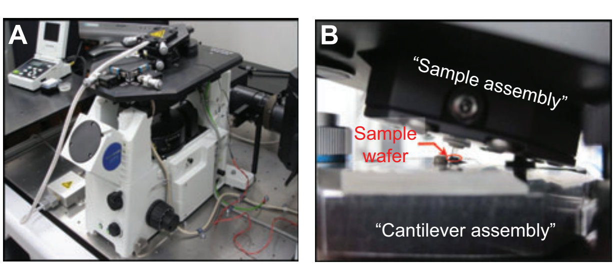


Figure 11 Picture of the HS-AFM system (Nano Live Vision by the Research Institute of Biomolecule Metrology).

Figure 15A shows the schematic representation of the high-power EUV-based resist contamination (HERC) analysis tool. It was set up at the beam line 9c (BL9c) in the NewSUBARU synchrotron radiation facility and used the 10.8-m-long undulator light source. A Ru (5 nm)-capped Mo/Si multilayer mirror was used as the WS. The WS was placed facing the resist-coated wafer. The undulator light was reflected on the WS to reach the wafer coated resist. The illumination intensities on the WS and the resist-coated wafer for the 13.5-nm wavelength were 267 mW/cm^2 and 85 mW/cm^2, respectively. The exposure chamber was pumped to ultrahigh vacuum conditions, i.e., $2\sim4\times10^{-6}$ Pa, without exposure to ensure a clean analysis environment. Figure 15B shows the schematic of the EB-based resist contamination analysis tool, named EUVOM-9000 (made by Litho Tech Japan). Two electron guns with 5 keV and 0.9 keV acceleration voltages were set up for the resist and the WS exposure, respectively. The WS consisting of 50-nm-thick Ru on the silicon substrate was positioned alongside the resist-coated wafer. The base pressure increased to $1\sim2\times10^{-5}$ Pa during the exposure due to the outgassing. These measured pressure values were similar to those obtained during the experiments at the HERC analysis

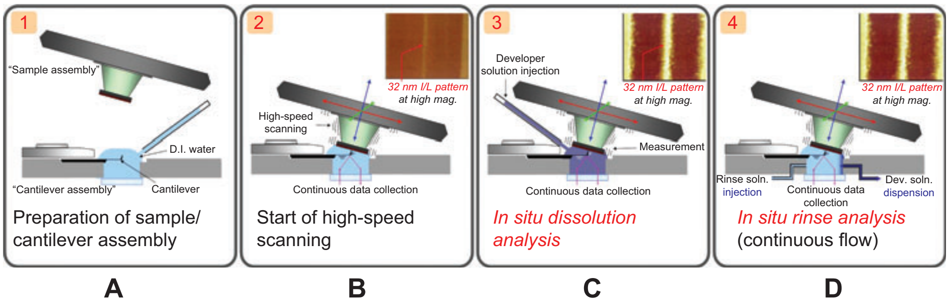


Figure 12 *In situ* dissolution analysis results obtained for PAG-blended.

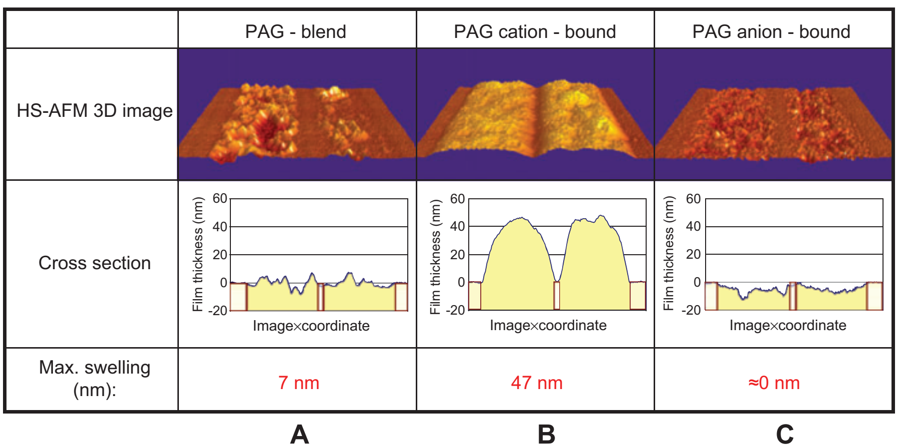


Figure 13 *In situ* dissolution analysis results obtained for PAG-blended, PAG-cation bound, and PAG-anion bound acryl-based resists as the demonstration of this method.

tool. The carbon-like contaminants on the WS surface was cleaned up by the cleaning unit of the EUVOM-9000 that consists of a hotwire filament and a hydrogen gas source.

The preliminary correlation study between the EUV and the EB was carried out by utilizing five sample resists shown in Figure 16. They had various

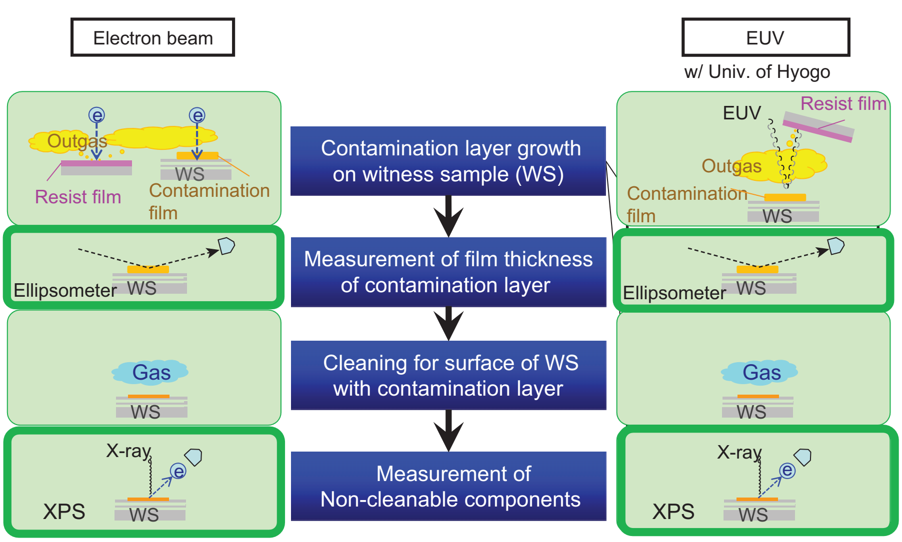


Figure 14 Resist outgassing qualification protocol based on the WS method.

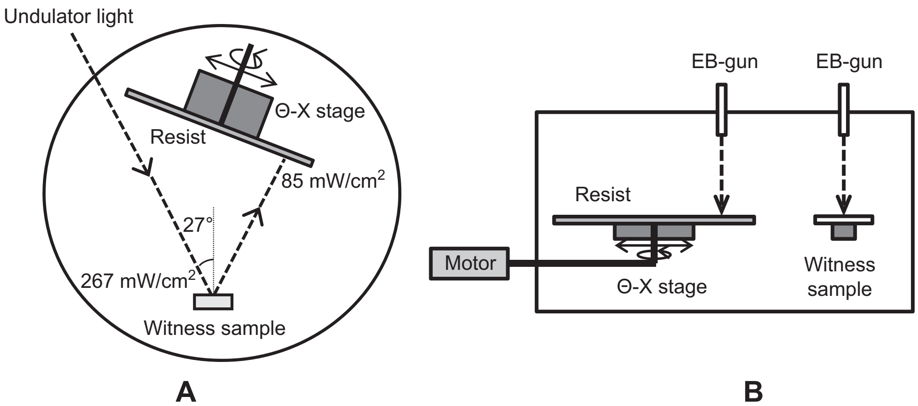


Figure 15 Schematic representation of the outgas test setup, (A) HERC analysis tool, (B) EB-based resist contamination analysis tool, named the EUVOM-9000 (made by Litho Tech Japan).

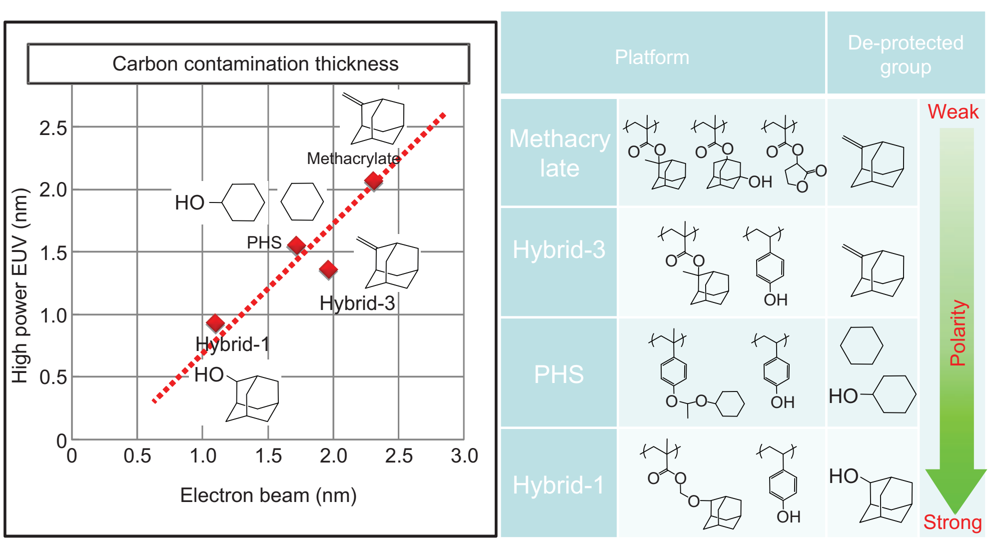


Figure 16 Preliminary correlation study between the EUV and the EB.

polymer platforms and protecting groups, which were polyhydroxystyrene (PHS), methacrylate, and PHS-methacrylate hybrid polymer (Hybrid). The linear correlation for carbon contamination between the EUV and the EB was clearly observed. It is also found that the carbon contamination was decreasing with the increase in the degree of polarity of the de-protected groups and polymer platforms. The possible speculation to describe the phenomena is that the de-protected group moves less freely in the resist film and has a less chance to outgas as the stronger polarized species have stronger interactions with the stronger polarized regions of the polymer matrix. Polarity control is one of the key design parameters to reduce outgassing [23].

5 Summary

The current status, issue, and provision for the key infrastructures of the EUVL for sub-20-nm hp generation, especially for the inspection technologies for the EUV mask and the resist-related technologies have been dedicatedly discussed in this report. The ABI tool, a successor of the MIRAI-Selete accomplishment, is being prototyped with sufficient sensitivity and inspection time for the hp 16-nm technology node. The PI tool with the EB projection imaging system will enable the realization of sufficient sensitivity and cycle time for 16-nm technology node. The fundamental imaging performance and defect detection has been successfully validated. The fundamental research on the resist and its outgassing is successfully in progress by leveraging the SFET and the contamination test setup with the EUV light and the EB. The development of the EUVL infrastructure, i.e., mask inspection, resist, etc. in consortia is a reasonable approach for reducing the cost of precompetitive technology development. The outcome of the EUVL infrastructure development driven by worldwide research activities will definitely ensure the realization of EUV lithography.

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