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Current Status of Extreme Ultraviolet Lithography in Japan

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Abstract: ASET, Association of Super-advanced Electronics Technologies, has been taking the initiative in developing EUV lithography technology in Japan for the past three years. The aspherical mirror metrology using a visible light point diffraction interferometer (PDI), the wave-front measurement using an at-wavelength PDI, and an at-wavelength reflectometry for multilayers, various imaging simulations, multilayer coatings for the mask, the development of absorber materials for mask patterning, the mask substrate cleaning technique, and various photoresist processes have been developed. The visible light PDI employs a 0.5-μm pinhole as an aperture to generate an ideal spherical wave-front and can measure a 0.3-NA mirror maximum. The at-wavelength PDI can measure the wave-front error of the projection optics. The at-wavelength reflectometer can measure the reflectivity of multilayers and the round-robin test is taking place among ASET, the ALS in Lawrence Berkeley, and BESSY in Germany. The mask cleaning technique employs a supersonic hydro-cleaning technique. We have confirmed that the single layer resists can be used for EUV lithography.

Key words: ultraviolet lithography; aspherical mirrors; alignment systems
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1 Introduction

ASET has been established in 1995, and Japanese government funded a total of 50 billion JPY from 1995 to 2000. Forty private companies, including foreign companies, participate in ASET now. ASET has been researching the semiconductor process technology, the magnetic storage technology, the full color reflective liquid crystal display, the semiconductor process equipment technology and the electronic system integration technology. ASET EUV Lithography Laboratory has been established in October 1998 in order to research EUV basic technologies for 70nm node and below, to catch up with EUV LLC and VNL in USA, to develop Japanese original technologies and to collaborate with USA and Europe. The head laboratory of ASET EUV Laboratory is located in Atsugi, Kanagawa Prefecture, and has two branch laboratories, with Sagamihara branch at Nikon Sagamihara plant and Himeji branch at Himeji Institute of Technology. We introduce the results and current status of our researches in this paper.

2 Why EUVL

EUV lithography is No. 1 candidate among the next-generation lithography technologies, EUV lithography, electron beam projection lithography,

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electron beam direct writing, LEEPL, proximity X- ray lithography and ion beam projection lithography. Table 1 shows the advantages and the disadvantages of each lithography technology. The lithography technology evolves from full- wafer exposure type to partial field exposure type in order to get a good overlay and a good usable DOF. Full - wafer exposing tools are a contact wafer aligner and a proximity wafer aligner, and next, a mirror projection aligner that has a ring field exposing area and exposes a wafer by one scanning, a step and repeat system called a wafer stepper has a 15mm × 15mm - 22mm × 22mm exposing area, and a step and scan system called a wafer scanner has about 25mm × 8mm field and is employed by the current KrF or ArF system. In Table 1, IPL, PXL and LEEPL use step and repeat systems. They go against the time, so we don't think they will be the mainstream of NGL.

Table 1 Comparison of NGL

	Resolution	Throughput	Critical Issues
EUVL	< 30nm	> 80wph (source dependent)	Source, Mask defect
EPL	≈ 50nm	≈ 10wph (conflict with resolution)	RES vs. TP, Wafer thermal expansion
EBDW	< < 30nm	< 10wph	TP
LEEPL	< 50nm?	> 10wph	1X Mask
PXL	< 70nm	< 10wph	1X Mask
IPL	< < 30nm	?	PO, Large Stencil Mask

EUVL uses a step and scan system, EPL uses a step and stitch system, and EBDW uses a direct writing system. A direct writing system is an ultimate exposing system, but it takes a very long time to expose a wafer even if a multi- column system is used, and the throughput conflicts with the resolution. The throughput of EPL system also conflicts with its resolution, so it will not be used for the mass production of memories or processors except for contact layers. Therefore EUVL is the only lithography technology that is used for mass production in 50- nm node and below by a process of elimination, but its source and mask defect are very critical issues.

3 Key issues of EUV lithography

A schematic drawing of an EUV scanner is shown in Figure 1. The described source is a laser produced plasma source, and the condenser optics and the projection optics are simplified, and the body structure and a vacuum chamber are not described.

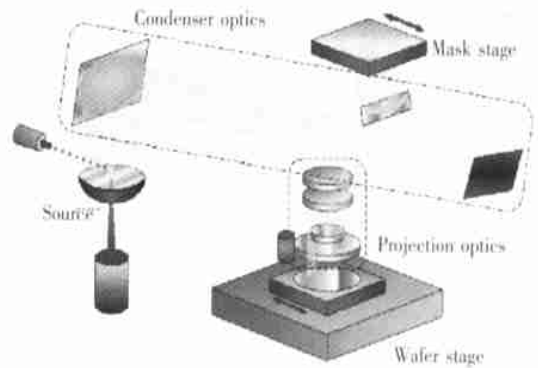


Fig. 1 A schematic drawing of an EUV scanner.

Source issues, power, debris and thermal loading are very critical. Mask issues, defect-free substrates, defect-free multilayers and defect inspection technique are critical too. Masks that satisfy a required flatness must be supplied at commercial prices. Projection optics issues, mirror fabrication, mirror metrology, multilayer coatings, phase shifting by multilayers, mirror holding, thermal deformation and chemical contamination are of concerns. Condenser optics issues, intensity uniformity, coherence factor uniformity, manufacturability and chemical contamination are of concerns.

4 Aspherical mirror metrology

Fizeau interferometers are widely used for measuring DUV projection lenses, because they have high productivity, sufficient accuracy and sufficient precision. On the other hand, a point diffraction interferometer (PDI) employs a nearly

ideal spherical wave diffracted by a small aperture such as a fiber or a pinhole, and is expected to have higher accuracy than Fizeau interferometers that utilize reference surfaces. When an aspherical mirror is measured, some compensation elements, such as a null lens or a computer-generated hologram, are generally used. However, such elements should not be employed on a PDI, because they will decrease the accuracy of the PDI. Fortunately, EUV aspherical mirrors have an approximately 10mm departure from a sphere at large; thus, the PDI is able to measure the aspherical surface without the use of any compensation elements. The EUV laboratory of ASET has developed an advanced point diffraction interferometer that aims at 0.2nm rms accuracy. Some features of this apparatus and related data are reported below.

4.1 Design concept

Figure 2 shows a rough sketch of the principle of the PDI. A nearly ideal spherical wave diffracted by a small aperture is divided in half: one being a reference light and the other, a testing light. The testing light is reflected by the tested surface with surface figure information and focuses on the aperture; then, it is reflected by the aperture surface. The reference light diffracted by the aperture and the testing light reflected by the aperture surface are relayed to a CCD image sensor and interference patterns are observed. The surface of the CCD image sensor is a tested mirror surface conjugate. Interference patterns include information of the tested surface figure, and the tested surface figure can be reconstructed from phases at each point.

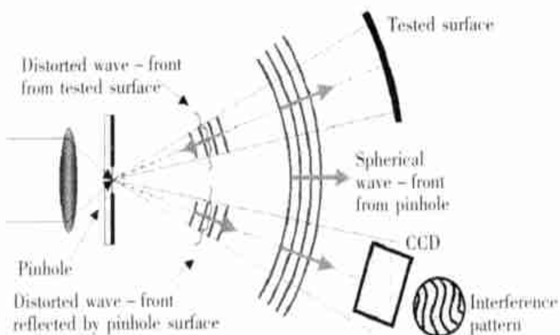


Fig. 2　Rough sketch of the principle of the PDI

Since the phases of static fringes can hardly be detected with high accuracy, the phase shifting method is adopted. The distance between the small aperture and the tested surface is varied over some wavelength range, and phases at each point on the CCD change synchronously with phase shifting. The design concept aims at realizing high accuracy, high precision and flexibility of use with various EUV mirrors.

4.2 Minute opening

Candidates for small aperture are the exit ends of an optical fiber and a pinhole. The optical fiber has the advantage of easy alignment for small wavefront aberration emitted from the aperture. In the case of the pinhole, the aberration of objective lens, the unroundness of the pinhole, and the misalignment between the spot and the pinhole cause wavefront aberration. The testing light reflected by the tested surface focuses on the aperture surface, and shift of the spot from the aperture also affects the accuracy of PDI. Nevertheless, the divergence angle of fiber-emitted light is insufficient to measure 0.3 N.A. mirrors. Therefore, a pinhole is employed on this PDI.

Table 2　Influence of error factors of pinhole on wave-front aberration of emitted light

Error factor	Tolerance	Error (nm rms)	
		$\varphi 1\mu m$	$\varphi 0.5\mu m$
Aberration of objective lens	0.05λ rms coma	0.01	< 0.005
Incident spot shift to pinhole	< 50nm	0.04	0.01
Mirror reflected spot shift to pinhole	< 100nm	0.05	< 0.01
Roundness of pinhole	< 20nm	0.02	0.01

Measurement errors due to pinhole-related wavefront aberrations are shown in Table 2. Pinholes with 1.0μm and 0.5μm diameters are considered. The numerical aperture of the objective lens

is 0.4, and the tested mirror has 0.2-numerical aperture surface. A pinhole with 0.5μm diameter has a clear advantage over that with 1μm diameter.

4.3 Auto pinhole alignment

A schematic drawing of the pinhole alignment system is shown in Figure 3. A pinhole with 0.5μm diameter is illuminated by an objective lens with 0.6-numerical aperture. The spot size is about 1μm longer than the diameter of the pinhole. The light reflected / diffracted by the pinhole returns, passes through a halfprism and irradiates a quadripartite detector. When the spot from the objective lens irradiates just the center of pinhole, the reflected light power becomes a minimum. As the incident spot position shifts, the reflected light power increases and the focused position on the detector moves.

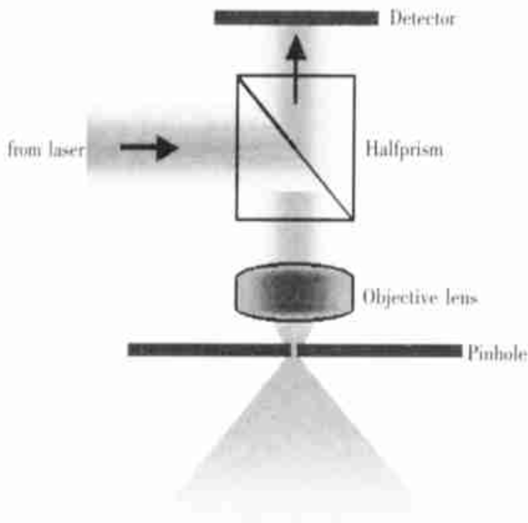


Fig.3 Pinhole alignment system

4.4 Helium environment

Point diffraction interferometers possibly have the disadvantage of measurement reproducibility compared to Fizeau interferometers. Generally, air fluctuation in non-common-path regions affects the reproducibility of interferometers. The space between the pinhole and the tested surface corresponds to this non-common-path region. The longest distance between the pinhole and the tested surface is 2,200mm in this PDI; therefore, the effect of air fluctuation will not be negligible. In order to reduce this air fluctuation, helium can purge the area between the pinhole and the tested surface. The refractive index of helium (n_{He}) is 1.000035, that of air (n_{Air}) is 1.000292 and $(n_{Air}-1)/(n_{He}-1) = 8.3$. The fluctuation effect of helium is expected to be eight times less than that of air.

A schematic drawing of the helium purging system is shown in Figure 4. Bellows connects the upper stage on which the PDI unit is mounted with the lower stage on which the tested mirror is mounted. Helium purging is executed by to- and -fro motion of the two stages, similar to an accordion. The density of helium exceeds 90% after two stage strokes.

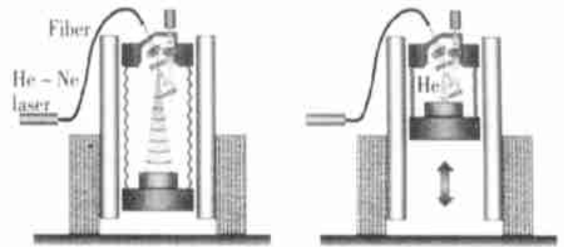
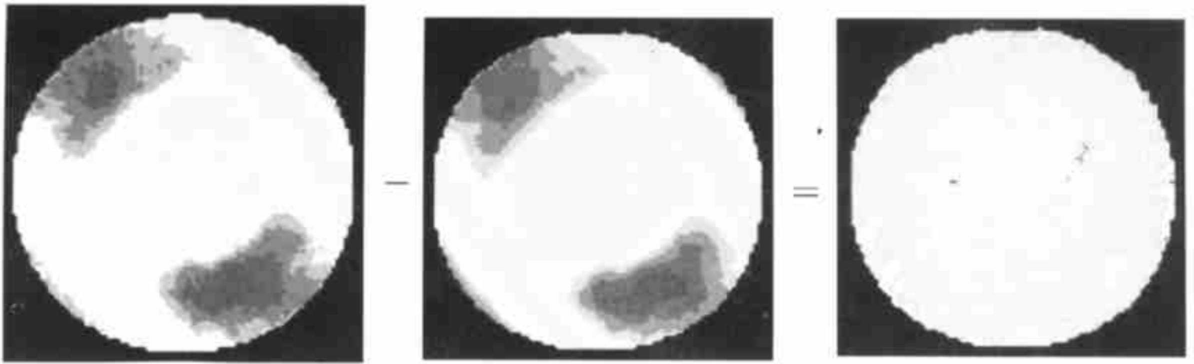


Fig.4 Helium purging system

4.5 Accuracy evaluation

It is extremely difficult to confirm the accuracy of an interferometer. To compare measurement results of different interferometers is easy, but the decision of the majority does not confirm their accuracy. Multiple measurement with several rotational angles of the mirror and the positional shift is also one method to confirm its accuracy, similar to tool-induced shift (TIS) measurement in registration measurement machines. This method is called "absolute measurement" here. Figure 5 shows the experimental results of absolute measurement, where a 1μm-diameter pinhole is used. The data show at least 0.23nm accuracy of this interferometer, but some long-term instability affects these data. Some improvement of stability is planned, and accuracy less than 0.2nm rms is expected with this PDI system.



One of the raw data　　Absolute measurement data　　System error: 0.23nm rms by Zernike fitting (Z1- 36)

Fig.5　Comparison of raw data and absolute measurement data

5　At-wavelength interferometry for projection optics

We have developed an at- wavelength PDI test stand for EUV projection optics; its principle is similar to the interferometer of Lawrence Berkeley National Laboratory. It uses the undulator beamline of New SUBARU in Himeji.

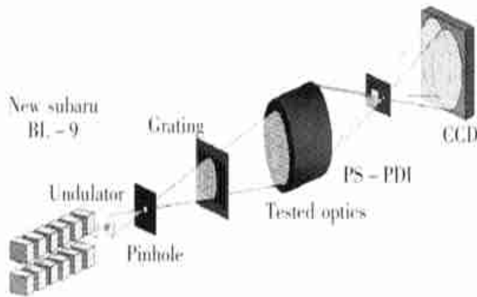


Fig. 6　Comparison of the raw data and the absolute measurement data

6　Mask development

We are developing multilayer coating technique, absorber layer materials and mask cleaning technique. Defect smoothing effect by multilayer coatings is observed with a magnetron- sputtering tool. It produces considerable defects, so we will start new experiments using an ion- beam sputtering tool.

We have developed mask- cleaning technique using supersonic hydro - cleaning (SHC) technique, described in Figure 7.

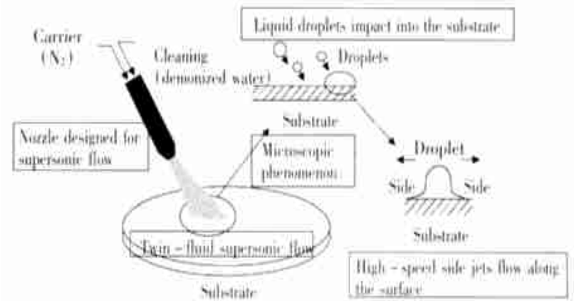
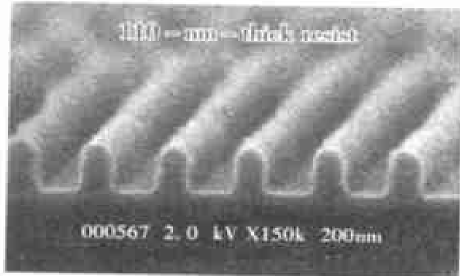


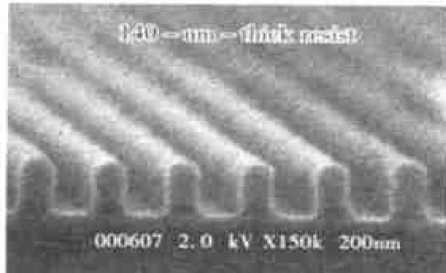
Fig.7　Schematic view of the supersonic hydro- cleaning (SHC) technique

7　Resist process

It used to be believed that EUV lithography would need surface imaging resist (silylation resist) or bilayer resist because EUV light is highly absorbed by almost all materials. But its transmittance is higher than 157- nm DUV light, and we have found that ultra- thin layer resist is available for EUV lithography, so resist issues is not critical now. Our experiments were carried out with the micro field exposure tool; it employs Schwarzschild optics, a critical illumination and light from storage ring. Figure 8 shows one of the results, of which pattern size is 70nm lines and spaces, and the resist

thickness is a parameter. We can see that 180- nm thickness ultra- thin resist can be used for EUV lithography, namely, neither top surface imaging nor bilayer resist is needed for EUV lithography.





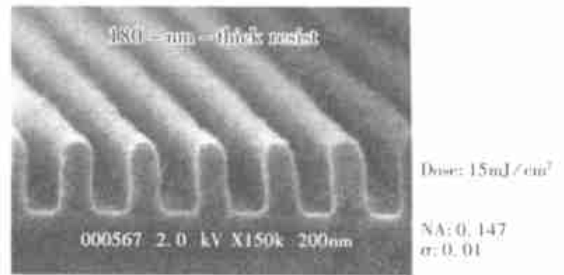


Fig. 8 Resist image vs. resist thickness with a positive KrF resist

8 Summary

ASET EUV Laboratory has been established in October 1998, and has obtained remarkable results. We have developed a visible light PDI system for aspherical mirrors, which has high precision and accuracy. We have developed an at- wavelength PDI system for projection optics, by which fundamental knowledge are obtained. We have developed multilayers and absorbers for mask. We have developed a mask cleaning technique, which uses supersonic hydro - cleaning technique. We have confirmed that single layer resists can be used for EUV lithography.

9 Acknowledgments

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