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Current Status of EUV Lithography

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Abstract: According to the SIA roadmap, by the year of 2006, minimum feature size of 70 nm on wafer is required. Research in U.S., Japan and Europe is aimed at developing and demonstrating an EUVL tool for critical feature size of 70 nm and below. In Japan, Himeji institute of technology (HIT) has developed an EUVL laboratory tool, which has a practical exposure field of 30mm × 28mm. The alignment and assembly of three aspherical-mirror optics were completed. A final wave-front error of less than 3 nm was achieved. Using this system, exposure experiments are performed using synchrotron facility of New Subaru. Up to now, 56nm patterns have been replicated in the exposure field of 10mm × 1mm. And using scanning stages, 100 nm L&S patterns have been replicated in the field of 10mm × 5 mm.

Key words: EUV lithography; aspherical mirrors; multilayer coatings
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1 Introduction

The technical requirements of the 21st century are accelerating the development within the semiconductor industry. There are several candidates for the 0.1μm generation of lithography that will be used on semiconductor production lines. Of particular note is EUVL, which has the potential to handle feature sizes from 0.1μm all the way down to 0.01μm.

Since 1984, we have been developing an EUVL exposure tool to clarify its capabilities. During the period from 1984 to 1992, we demonstrated the feasibility of replicating 0.1-μm patterns using multilayer-coated Schwarzschild optics[1]. From 1992 to 1995, we worked on developing a 2-aspherical-mirror system with an exposure field large enough for practical use (20 mm × 25 mm), and succeeded in replicating patterns in a large exposure field of over 10 mm × 12.5 mm[2-3]. This exposure tool had scanning stages, but the alignment optics was never developed. In the third stage of EUVL development, we have built an EUVL laboratory tool with practical exposure field and alignment optics for mask and wafer to clarify the device fabrication process[4-6]. It operates at a wavelength of 13.5 nm and employs a three-mirror imaging system with a numerical aperture of 0.1. It is capable of replicating 60-nm patterns in a 30mm × 1mm area. This work has been carried out with the collaboration of the Association of Super-advanced Electronics Technologies (ASET) and Nikon.

In U.S., an EUVL tool called Engineering Test Stand (ETS) was completed in the year 2000 at EUV-LLC with the cooperation of LLNL, LBNL, and SNL. This tool will operate at a wavelength of 13.4nm and will employ a four-mirror imaging system with a numerical aperture of 0.1[7]. Up to now, the alignment of optics using the point diffraction interferometer of both at-wavelength and visible light was completed. The wave-front error of less than 1.0 nm was achieved.

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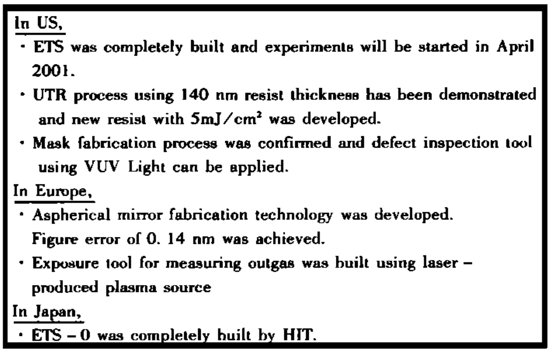
In Europe, the EUCLIDES program (Extreme UV Concept Lithography Development System) headed by ASM Lithography (ASML), partnered by Carl Zeiss and Oxford Instruments is evaluating EUV lithography from August 1998. This program focuses on the mirror fabrication, high reflectivity multilayer coatings, resist outgassing mitigation and vacuum stages[8]. (Fig. 1)



In US,

- **ETS was completely built and experiments will be started in April 2001.**
- **UTR process using 140 nm resist thickness has been demonstrated and new resist with 5mJ/cm² was developed.**
- **Mask fabrication process was confirmed and defect inspection tool using VUV Light can be applied.**

In Europe,

- **Aspherical mirror fabrication technology was developed. Figure error of 0. 14 nm was achieved.**
- **Exposure tool for measuring outgas was built using laser – produced plasma source**

In Japan,

- **ETS – 0 was completely built by HIT.**

Fig. 1 Status of EUVL

This paper briefly describes the three- mirror EUVL Laboratory Tool installed in New Subaru at HIT and presents the current status of some key technologies.

2 Status of key technologies

2.1 Source

First, we have to determine the EUV power needed to meet the specifications of a 0. 1μm generation machine. Table 1 shows the requirements of the 0. 1μm generation tool and the condition of imaging and illumination optics.

To obtain a throughput of 80 wafers per hour, an EUV power of over 61. 1 W is needed. Currently, two types of sources are being investigated for EUVL: a synchrotron radiation source (SR) and a laser plasma source (LPS).

SR is a debris- free and clean source. However, to obtain the high throughput shown in Table 1 is so difficult that the photon flux at the wavelength of 13. 5 nm is low. Figure 2 shows a graph of flux density vs. wavelength for the New Subaru storage ring[4]. Assuming a bandwidth of 3% for a Mo/Si multilayer, a current of 500 mA, and a collection angle of 40 mrad (H) × 3. 8 mrad (V), the incident power is estimated to be about 0. 4 W. To obtain a satisfactory throughput using a SR source, a photon flux of New Subaru has to be up to 150 times. Thus, the acceptance angle, which may be 10 times wider, has to be considered, and the wigglers which may be 8 or 10 times shorter has to be developed. It needs to push the current as well.

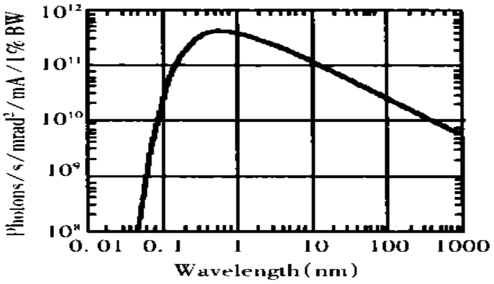


Fig. 2 Photon flux at New Subaru

On the other hand, LPS is compact and compatible with the conventional equipment on a production line for semiconductor devices.

In order to satisfy the specifications, LPS requires a laser power of about 6 kW, assuming conversion efficiency for LPS of 1%. It means that the laser must have a high power of, say, 1. 0 J/pulse and a high repetition rate of 6000 Hz.

Up to now, using a Xenon cluster target at SNL an EUV power of about 15w/4pai is achieved with a TRW laser system delivering an output power of 1. 7 kW. This system satisfies a debris-free, recycling Xe gas and high efficiency.

2.2 Projection optics

The optics for EUVL consists of illumination and imaging optics. During the past few years, a great deal of work has been done on optics design. Table 2 shows the specification of EUV Lab Tool developed by HIT and EUV- LLC.

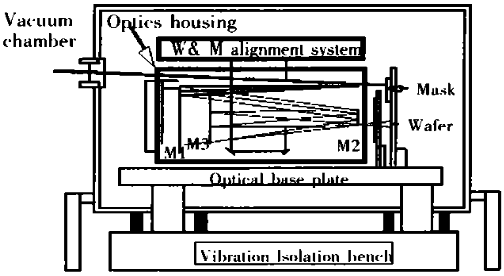


Fig. 3 EUVL laboratory tool

Figure 3 shows the configuration of the HIT system[4-6], and Figure 4 is a photograph of the HIT EUVL tool. The whole system consists of illumination optics, mask and wafer scanning stages, mask and wafer alignment optics, a reduction camera, and a load- lock chamber for loading wafers. The aspherical mirrors of the projection camera were fabricated from Scott- Zerodur material by SVG- Tinsley.

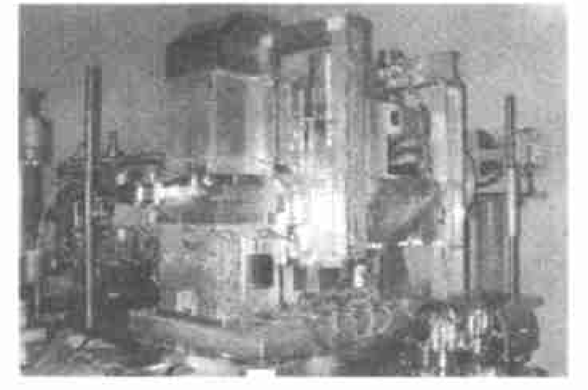
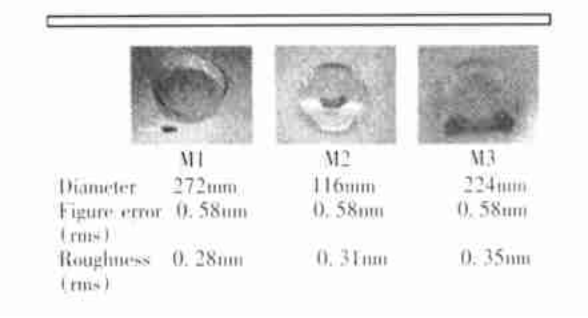


Fig. 4 Photograph of the HIT EUVL tool

An allowable figure error to achieve a diffraction- limited resolution of an optical system is provided by Rayleigh' s quarter wavelength rule and the Marechal condition. This tolerance gives $\lambda/4n$ peak- to - valley (P- V) and $\lambda/28\sqrt{n}$ rms for each mirror of the three-mirror system, they are 1. 1nm P- V and 0. 28 nm rms for at the wavelength of 13. 5nm in our image optics. The requirement of surface roughness of mirror is defined by the Debye-Waller factor. If the reflectivity down to 90% of the theoretical value is permitted, the requirement of surface roughness estimated to be less than 0. 33nm. Figure 5 shows the configuration of aspherical mirrors developed. M1 is a concave primary mirror 272mm in diameter; M2 is a convex secondary mirror 116mm in diameter; and M3 is a concave tertiary mirror 224mm in diameter. M1, M2 and M3 have a maximum asphericity of 27 μm, 81 μm, and 10 μm, respectively. The aspherical axis of each mirror is centered with respect to the physical diameter, and the clear aperture is off - axis.



	M1	M2	M3
Diameter	272mm	116mm	224mm
Figure error (rms)	0. 58nm	0. 58nm	0. 58nm
Roughness (rms)	0. 28nm	0. 31nm	0. 35nm

Fig. 5 Aspherical mirror for the imaging optics

Aspherical polishing was done by Tinsley' s computer- controlled optical surfacing (CCOS) method. CCOS uses a combination of sub- aperture polishing tools to iteratively polish small areas of the surface. After CCOS polishing, the final figure precision of each mirror was measured by means of calibrated interferometric tests.

The interferometer had a Twyman- Green interferometer configuration, and a computer- generated hologram (CGH) was also used to provide an aspherical shape for use as a standard. The final figure error was 0. 58 nm over the clear aperture, as measured using the CGH. These values are not satisfied the above requirement. It requires the higher precision fabrication and measurement.

The surface roughness was measured with a phase measuring microscope in an area of 160 μm x 120 μm. Several spots were measured over the clear aperture to obtain an average value. M1, M2, and M3 have an average roughness of 0. 28 nm, 0. 31 nm and 0. 35 nm rms, respectively. These values almost satisfied the specifications.

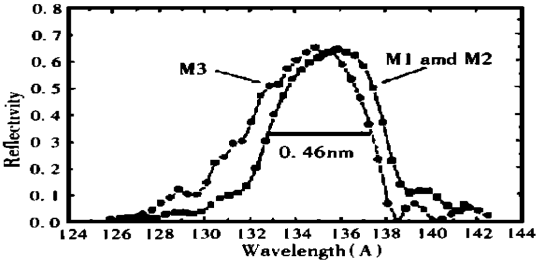


Fig. 6 Reflectivity of Mo/Si MLs for imaging mirrors

The mirrors are coated with a Mo/Si multilayer deposited by Osmic. However, for curved mirrors, the d- space matching of the coating has to be taken into account. That is, the center wavelength of the reflectivity of each mirror has to be matched within 0. 1 nm over the clear aperture of the mirrors. Since the incident angles of the mirrors are different in the area of the clear aperture, M1 and M2 require multilayer coatings with a thickness gradient in order to accommodate varying incident angles. However, for M3 the variation in the incident angle is small, enabling a d- uniform multilayer to be used. The coating conditions of M1 and M2 are the same. Figure 6 shows the experimental reflectivity of each witness sample measured by Osmic. The center wavelength of the reflectivity of M1 (M2) and M3 are 13. 54 nm and 13. 46 nm, respectively. The deviation of the center wavelength over the clear aperture is less than 0. 04 nm from 13. 5 nm. And the wavelength matching of over 0. 45 nm is obtained. This data is enough to get high throughput.

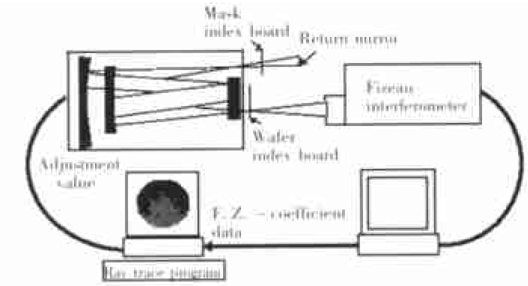


Fig. 7 Fine adjustment- outline

Optical alignment was performed using a Fizeau-type interferometer(Fig. 7). Up to now, a wavefront error of 3nm was achieved[9-11]. (Fig. 8)

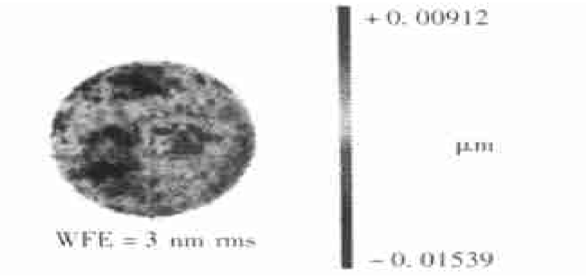


Fig. 8 Wave-front error

2.3 Mask fabrication

One of the key technologies is how to fabricate the defect- free reflective mask. Mask defects can occur either on the substrates before coating, opaque and clear defects on the absorber pattern and in the coating itself. The former two items are as same as optical lithography, but the latter one is the specific problem. The goal of defect number in the coating is less than 0. 001 defects/cm^2 at the size of 80 nm. LLNL has developed an ion beam sputter deposition equipment with super clean specification. Recently, the defect number of 0. 02/cm^2 on the 200- mm substrates was achieved using this system.

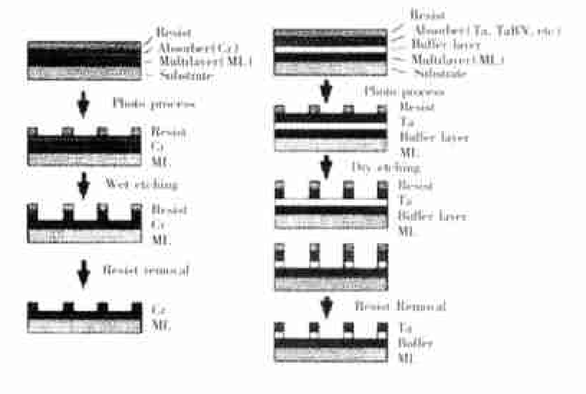
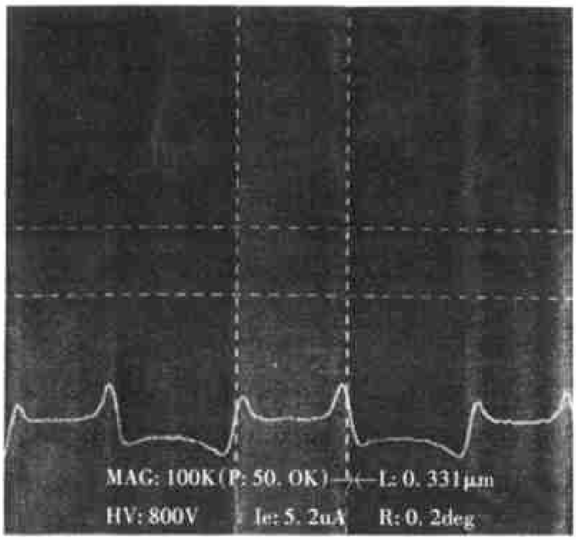
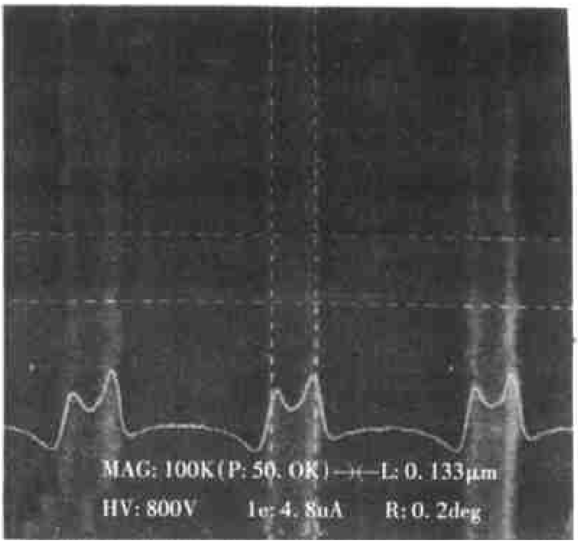


Fig. 9 Mask process

Absorber patterns are fabricated in the usual fashion of LSI process. Heavy metal materials such as Ta and Cr etc. can be employed. Presently, Cr absorber mask on glass substrate was fabricated by wet process in the generation of 0. 18 mm node lithography. If this mask fabrication process could be introduced in the EUVL mask fabrication, the mask fabrication cost for EUVL will be kept as same as that for KrF lithography. We have proposed the Cr absorber mask for EUVL and have fabricated the absorber pattern by the ordinary wet etching process. Figure 9 shows the fabrication process of Cr absorber mask for EUVL. At first, molybdenum (Mo)/silicon (Si) multilayer film has been deposited on Si wafer in diameter of 4 inches using a rf-enhanced plasma magnetron sputtering deposition system. Second, Cr film with the thickness of 100nm has been deposited on Mo/Si multilayer film substrate by using a DC sputtering deposition method. Third, the EB resist was coated and the resist mask patterns for the Cr absorber were fabricated by EB lithography process. Fourth, using resist pattern as a mask, Cr absorber patterns have been transferred by means of the wet etching process. Finally, resist was removed by using Piranha cleaning method. For a wavelength of 13.5nm, assuming the reflectivity of 60% at the incident angle of 87.95, the mask contrast of approximately 300 has been estimated. Figure 10 shows the absorber patterns fabricated on the Mo/Si wafer. 0.35 mm lines and spaces are clearly fabricated. Furthermore, the smallest figure size of 0.15mm are shown in Fig. 10(b). The characteristics of these pattern such as edge roughness was as same as that of absorber patterns for KrF Mask.



0.33μm L&S(1:1)



0.13 μm lines & 0.26μm spaces

Fig. 10 Cr absorber EUVL mask

2.4 Resist process[12]

The absorption coefficients of the resist materials are large at the wavelength of 13.5 nm. Thus, it is proposed mainly three kinds of resist material processing technologies for 1) the ultra thin single layer resist, 2) the silicon containing bi-layer resist, and 3) the silylation resist for top surface imaging. We have examined the sensitivity and penetration depth of commercially available DUV photoresists.

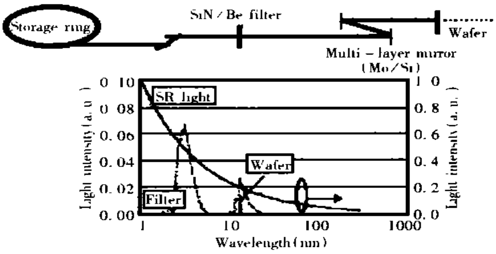
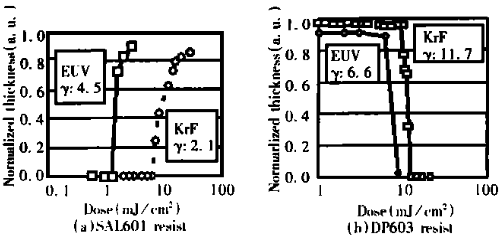


Fig. 11 Evaluation system of resist

An experimental setup for the EUV exposure and the spectra on a wafer are shown in Figure 11. The SiN/Be filter can cut off the longer wavelength region and two Mo/Si multilayer mirrors can cut off the shorter wavelength region.



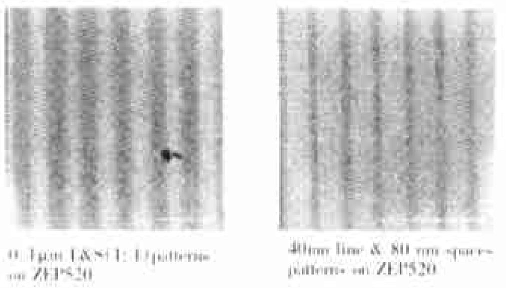
(a) SAL601 resist

(b) DP603 resist

Fig. 12 Sensitivity curves of chemical amplified resists

Figure 12. shows the sensitivity curve for the positive- tone chemical amplified resist of DP 603 and the negative- tone chemical amplified resist of SAL601. The sensitivities of DP603 and SAL601 are 9mJ/cm^2 and 2.0mJ/cm^2, respectively. These results show that the current resist for KrF lithography can be applicable for EUVL.

3 Exposure results[6-13]



0.1μm L&S (1:1) patterns on ZEP520

40nm line & 80 nm space patterns on ZEP520

Fig. 13 Replicated patterns using Cr absorber EUVL mask

Exposure experiments were performed on an SR beamline of the New Subaru ring. Figure 13 shows an exposure pattern. Mask with Cr absorber patterns fabricated by wet process was used. L&S patterns with feature sizes of 0.1μm were successfully replicated. And patterns with a width of 40nm, which is the diffraction- limited resolution of the optics, were resolved. Resist thickness was 135- nm. Fig. 14 shows an exposure pattern on a large field of 10mm × 5mm using the scanning stages. 100nm L&S patterns are clearly resolved in a direction of the scanning stages.

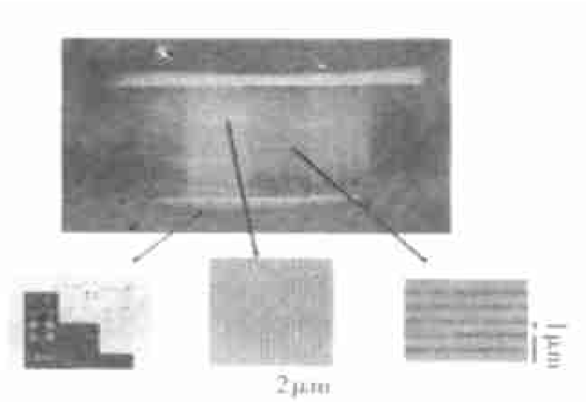


Fig. 14 Large exposure pattern (10mm× 5mm)

4 Conclusion

We have developed a three- aspherical- mirror optical system. The mirrors were fabricated using the CCOS process and a phase shift interferometer, and a figure error of 0.58nm and surface roughnesses of 0.3nm were obtained. M1 and M2 are coated with a graded d- spacing Mo/Si multilayer, and M3 is coated with a uniform d- spacing Mo/Si multilayer. The peak reflectivity of the mirrors is 65% at a wavelength of 13.5 nm. The wavelength matching of each mirrors spans 0.45 nm. The mirrors were aligned with a Fizeau- type phase shift interferometer, and a final wave-front error of less than 3 nm was achieved.

Exposure experiments carried out at the New Subaru synchrotron facility reveals that this system is capable of replicating 56nm patterns in a 10mm × 1mm exposure field and 100nm L&S patterns in a field of 10 mm x 5mm, respectively. These results demonstrate that we are approaching the goal of a practical EUVL system.

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