Current Status of EUV Lithography

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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) have developed an EUVL Laboratory Tool, which has a practical exposure field of 30 mm × 28 mm. The alignment and assembly of 3-aspherical mirror optics was 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, 56 nm patterns have been replicated in the exposure field of 10 mm × 1 mm.

Keywords: EUV lithography, aspherical mirror, multilayer coating

1. Introduction

The technical requirements of the 21st century are accelerating the developments within the semiconductor industry. There are several candidates for the 0.1- μm 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 0.1 μm all the way down to 0.01 μm . Since 1984, we have been developing an EUVL exposure tool to clarify its capabilities. In the period from 1984 to 1992, we demonstrated the feasibility of replicating 0.1- μm patterns using multilayer-coated Schwarzschild optics¹⁾. 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 3-mirror imaging system with a numerical aperture of 0.1. It is capable of replicating 60-nm patterns in a 30-mm × 1-mm area. This work has been carried out with the collaboration of the Association of Super-advanced

Electronics Technologies (ASET) and Nikon.

In the U.S., an EUVL tool called Engineering Test Stand (ETS) will be completed in the year 2000 at EUV-LLC with the cooperation of LLNL, LBNL, and SNL. This tool will operate at a wavelength of 13.4 nm and will employ a 4-mirror imaging system with a numerical aperture of 0.1⁷⁾. 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.

In the 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 stages⁸⁾.

This paper briefly describes the 3-mirror EUVL Laboratory Tool installed in New Subaru at HIT and presents 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 0.1- μm generation machine. Table 1 shows the requirements of the 0.1- μm generation tool and

the condition of imaging and illumination optics. To obtain a throughput of 80 wafers per hour, an EUV power of over 13.1 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 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 1 shows a graph of flux density vs. wavelength for the New SUBARU storage ring⁴⁾. Assuming a band width of 3% for a Mo/Si multilayer, a current of 500 mA, and a collection angle of 40 mrad (H) $\times$ 3.8 mrad (V), the incident power is estimated to be about 0.27 W. The throughput calculated on the basis of this value is roughly 1.8 wafers/hour. To obtain a satisfactory throughput using an SR source, a photon flux of New SUBARU has to be up to 50 times. Thus, the acceptance angles 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.

Table 1. Requirement of EUV source power

Specification of 0.1 μ m generation	Production Tool
Field size	25 mm x 40 mm
Wafer diameter	300 mm
Resist Sensitivity	10mJ/cm ²
Throughput	80 wafers/hour
EUV Power on Wafer	250mW
Transmission of mask and optics	0.135
Number of mirrors	4
Multilayer Reflectivity	0.67
EUV power on mask	1.85W
Transmission of illumination optics	0.13
Number of mirrors	4
Reflectivity of mirrors	0.85
Filter transmission	0.5
Net condenser efficiency	0.5
Power required	14.2W

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 1.4 kW, assuming a conversion efficiency for LPS of 1%. That means that the laser must have a high power of, say, 0.5

J/pulse and a high repetition rate of 3000 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 satisfied a debris-free, recycling Xe gas and high efficiency.

Fig.1. Photon flux of New SUBARU ring

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 Labo. Tool developed by HIT and EUV-LLC.

Table 2. Specifications of EUVL Lab Tool

	HIT	EUV-LLC
Numerical aperture	0.1	0.1
Magnification	1/5	1/4
Resolution	0.06	0.07
Depth of focus@0.1 μ m	1.9	1.5
Ring field on wafer	30mmx 1mm	24mmx1.5mm
@ scanning-mode	30mmx28mm	24mmx32.5mm
Mask size	8 inch	8 inch
Wafer size	8 inch	12 inch
Number of mirror	3	4
Exposure wavelength	13.5 nm	13.4 nm
Source	SR	LTP

Figure 2 shows the configuration of the HIT system⁴⁻⁶⁾, and Figure 3 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-

Fig.2. The configuration of HIT EUVL system

Fig.3. The photograph of HIT EUVL system

Zerodur material by SVG-Tinsley.

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 $\lambda=13.5$ nm 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 4 shows the configuration of aspherical mirrors developed. M1 is a concave primary mirror 272-mm in diameter; M2 is a convex secondary mirror 116-mm in diameter; and M3 is a concave tertiary mirror 224-mm in diameter. M1, M2 and M3 have a maximum asphericity of 27 . m, 81 . m, and 10 . m, respectively. The aspherical axis of each mirror is centered with respect to the physical diameter, and the clear aperture is off-axis.

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.

(a) M1 mirror

(b) M2 mirror

(c) M3 mirror

Fig. 4. The photograph of aspherical mirrors

The interferometers 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 . m x 120 . m. 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.

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 same. Figure 5 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.

Optical alignment was performed using a Fizeau-type interferometer. Up to now, a wave front error of 3 nm was achieved⁹⁻¹¹⁾.

Fig.5. Reflectivity of each mirror

2.3 Mask fabrication

Table 3 shows the requirement of reflective mask for 100-nm and 70-nm generation. 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 0.001defects/cm² 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/cm² on the 200-mm substrates was achieved using this system. Absorber patterns are fabricated in the usual fashion of LSI process. Heavy metal materials such as W, Ti, Ta and Cr etc. can be employed.

Table 3. Requirements of EUVL Mask

Year	2006	2009
Technology Generation	100 nm	70 nm
DRAM size	16G	64G
MFS (MPU Gate: nm)	70	50
Field Size(mm x mm)	25 x 40	25x 44
Magnification	1/4	1/4
Mask Size(mm)	230	230
Mask MFS(nm)	280	200
Image Placement(nm)	20	16
CD Uniformity(nm)	9	6
Defect Size(nm)	80	60

2.4 Resist process¹²⁾

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 photo resists.

Experiment setup for the EUV exposure and the spectrums on a wafer are shown in Figure 6. The SiN/Be filter can cut off the longer wavelength region and two Mo/Si multilayer mirrors can cut off the shorter wavelength region.

Figure 7. 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/cm² and 2.0mJ/cm², respectively. These results show the current resist for KrF lithography can be applicable for EUVL.

3. Exposure results⁶⁾

Exposure experiments were performed on

an SR beamline of the New Subaru ring.

Fig.6. Experimental setup and the spectrum

(a) DP603 resist

(b) SAL601 resist

Fig. 7. Measured sensitivity of resists

Figure 8 shows an exposure pattern. Mask with Ni absorber patterns fabricated by electroplating was used. Patterns with feature sizes of 0.1 μ m, 0.08 μ m, and 0.056 μ m were successfully replicated. In the figure, it can be seen that the line edge roughness becomes worse as the pattern becomes finer. In these experiments, patterns with a width of 56 nm, which is the diffraction-limited resolution of the optics, were resolved. Resist thickness was 135-nm.

Fig.8. Exposure patterns

4. Conclusion

We have developed a 3-aspherical-mirror optical system. The mirrors were fabricated using the CCOS process and a phase shift interferometer, and a figure error of 0.58 nm and surface roughnesses of 0.3 nm 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 wavefront error of less than 3 nm was achieved.

Exposure experiments carried out at the New Subaru synchrotron facility revealed that this system is capable of replicating 56-nm patterns in a 10 mm x 1 mm exposure field. These results demonstrate that we are approaching the goal of a practical EUVL system.

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