The Early Days of R&D on EUV Lithography and Future Expectations

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Extreme Ultraviolet Lithography (EUVL) is will soon be fully practically applicable to the high volume manufacture of semiconductor chips. This paper describes the establishment of soft X-ray or EUV optical technology utilizing multilayer optical elements and the early stages of research regarding its application as a lithographic technique. The technology was established through the demonstration of three fundamental properties of optics: imaging, interference, and polarization in the soft X-ray region by multilayer optical elements. In imaging optics, we have demonstrated EUVL’s feasibility as a lithographic candidate by establishing a design employing two-aspherical mirror optics, processing the aspherical mirrors with a multilayer coating, devising an assembly technology for imaging optics, and realizing an illumination system for large exposure area. This result showing the possibility of large-area exposure constitutes an epoch that strongly promotes the practical application of EUVL. Also, at-wavelength metrology in the EUV wavelength region, such as mask inspection based on a Mirau interferometric microscope, or thin film analysis based on a soft X-ray ellipsometer has contributed greatly to the practical application of EUVL.

Keywords: Extreme ultraviolet lithography (EUVL), Multilayer mirrors, Soft X-ray optics, X-ray interferometry, X-ray ellipsometry, At-wavelength metrology

1. Introduction

Over 120 years have passed since X-rays were discovered by W. C. Röntgen [1]. In the meantime, this mysterious invisible light has made a great contribution to human society. In the medical field X-ray photography and computerized tomography (CT) are now indispensable diagnostic techniques, and X-ray studies support the progress of science and technology in fields such as X-ray analysis. However, these applications merely make use of a few of the properties of X-ray light. Röntgen thought that an X-ray was a kind of light, despite it being invisible to the eye. He tried to confirm its light properties, such as refraction, reflection, polarization and interference, but was ultimately unsuccessful [2].

In the early days of Extreme Ultraviolet Lithography (EUVL) R&D, applications that made use of the properties of X-ray light had still not been developed nearly a century after its discovery. With respect to lithography technology, X-ray Proximity Lithography (PXL) is an extension of X-ray photography, it is to say shadowgraph rather than camera-based photograph. If we had a lens, it would have been possible to realize a very high-resolution camera by taking advantage of the fact that the wavelength of an X-ray is two orders shorter than that of visible light.

Since the discovery of X-rays, the light source has also progressed greatly from the X-ray tube. In particular, the appearance of synchrotron radiation [3] has offered a major opportunity. On the other hand, a major obstacle to utilizing X-rays as optics is that they do not bend (not refract). This is because the refractive index of most materials in the X-ray region is very slightly smaller than 1, which is the value of a vacuum, and the difference depending on the material is very small. Furthermore, the absorption of X-rays by most materials is generally large, and there is no transparent substance as in the visible light region. For this reason, the refraction type optical elements such as lenses and prisms widely used in the visible light region cannot be used in the X-ray region.
The idea of a multilayer mirror with an artificial periodic structure that appeared in the 1970s [4], solved the problem of obtaining a light source in the soft X-ray region, but no optical element was available. With the development of multilayer mirrors, the possibility arose of designing a high resolution optical system with near normal incidence and realistic reflectance [5,6], and the possibility grew of obtaining imaging optics in the X-ray region.

The first application of multilayer coated optical systems was in the scientific field, for example, the X-ray telescope [7] and the X-ray microscope. Applications to lithography technology, which required shorter wavelength light sources to produce more highly integrated semiconductor chips, attracted great interest from industry. Takenaka has summarized the research history of multilayer mirrors for soft X-ray optics in detail [8].

Although the emergence of light sources and expectations as regards the possibility of realizing optical imaging systems by using multilayer mirrors increased, there were many engineering problems in terms of lithography applications. This paper describes the establishment of soft X-ray or EUV optical technology utilizing multilayer optical elements and the early stages of research regarding its application as a lithographic technique.

2. Progress of multilayer fabrication technologies

In 1989, when I started to study soft X-ray optics based on multilayer mirrors, the reflectance of a multilayer mirror was about 40%, which was about 60% of the value expected from the calculation [9]. To investigate and clarify the cause of the deviation from the theoretical value, multilayer films were evaluated from all angles. Transmission electron microscope (TEM) observations of Mo/Si multilayer film showed that the Mo layer was microcrystalline, the Si layer was amorphous, and furthermore, a thin silicide layer was formed by the diffusion of Si at the interface. It was found that the reflectance was reduced by a loss of steepness at the interface of the multilayered film due to roughness and diffusion. Since the interface roughness of multilayer film is attributable to the crystal grain boundary of refractory metal elements such as Mo, we proposed the use of eutectic alloying as an active amorphization method. The realized MoRu/Si multilayer film was nearly perfectly amorphous, and achieved a reflectance that was close to 80% of the calculated value.

To measure the soft X-ray reflectivity with high precision, a spectrometer and a reflectometer were designed, manufactured and installed on beamline BL-1 at the Photon Factory in the National Laboratory for High Energy Physics. Feedback to multilayer fabrication from high precision reflectance measurements using soft X-rays greatly contributed to the advance of multilayer fabrication technology. These studies made it possible to routinely fabricate multilayer mirrors with a reflectance of 65% in Mo/Si [10].

Furthermore, high intensity X-rays are assumed to be present in the multilayer mirrors of the reflective mask and the illumination collector mirror, and there was concern that the heat resistance of the multilayer film would become a problem [11]. A series of studies on this problem revealed that the diffusion of Si at the interface becomes conspicuous in Mo/Si multilayer film at a high temperature of 400°C or more, silicide is formed at the interface, and the reflectance rapidly decreases [11]. To suppress the formation of a metal compound at the interface, a stable compound (for example, B₄C, SiC, or BN) was used as a light element [11,12], or 0.3nm-thick carbon barrier layers were intercalated at the interface between the Mo and Si layers [13,14]. These measures have confirmed that the multilayer films are stable even at a high temperature of 400 °C or more. Thus, multilayer mirrors with high heat resistance were realized.

Next, a sub-nanometer precision is required for the substrate used for EUVL, which leads to problems such as the deformation of the substrate due to the residual stress of the multilayer film and, in the worst case, peeling of the multilayer film. In general, tensile stress is generated when a refractory metal, such as Mo used for a multilayer film, is formed by sputtering, and a strong compressive stress is generated in an amorphous film such as Si. By optimizing such conditions as the RF power at film deposition, we found a method for controlling the stress from near zero to slightly tensile that was suitable for self-support without impairing the reflectance of the multilayer mirrors [15,16].

The ability to freely control the stress of the multilayer film increases the possibility of obtaining a transmission type element in which the multilayer film itself is freestanding. If a transmission type element can be realized, it becomes possible to use basic optical elements such as a beam splitter to induce the transmitted light and reflected light to interfere. In addition, a transmission type polarizer utilizing the fact that the pseudo Brewster angle of the multilayer film periodic structure is about 45
degrees can be realized. However, to realize a fully self-supporting multilayer film, we must establish both stress control and a process of reducing the surface roughness of the supporting membrane used as the initial deposition substrate and the complete removal by dry etching of the supporting membrane. All these problems were solved by adopting an ECR-plasma CVD SiC supporting membrane with a very smooth surface and using Ru with a high etching resistance to the etching gas of the supporting membrane for the layers of the multilayer mirrors. Finally, a 1:1 beam splitter with a flatness of 1nm at a 10mm square aperture and a transmittance and reflectance of 27% at a wavelength of 13.4 nm has been realized [17,18].

In this way, the technology for a multilayer mirror has been developed and opened the way for the imaging, interference and polarization applications described later.

3. Application to EUVL as an imaging optics

In this section, we will describe the time from the early days of R&D on EUVL to the demonstration of large area exposure. Research on soft X-ray reduction lithography was started by Kinoshita of NTT in around 1984. The first demonstration of pattern replication using Schwarzschild optics was reported in 1986 [19]. In the latter half of the 1980s, a feasibility demonstration of diffraction limited performance in a small exposure area using the Schwarzschild optics was undertaken in Japan [20] and the United States. In response to the achievement of a diffraction limit performance by AT&T Bell Laboratories in 1990 [21], the focus of the research has shifted to the design of imaging optics to ensure a practical chip area.

For the optical design, a ringfield scanning exposure method was essential to ensure a practical chip size. The resolution of the optical system is given by Rayleigh's equation. As the wavelength becomes shorter and the numerical aperture (NA) becomes larger, the resolution increases. On the other hand, as the NA increases, the depth of focus decreases, and so there is an optimum range of exposure wavelength and NA for a practical lithography system [20]. Furthermore, to increase the NA, it is necessary to increase the number of mirrors, and there is a trade-off between the number of mirrors and the system throughput based on the multilayer mirror reflectance. In consideration of these conditions, the imaging optical system selected an NA of 0.1 with a minimum of two mirrors. To realize a system with a minimum number of mirrors, a mirror an aspherical surface was adopted. When the NA is 0.1, the optimal exposure wavelength is 4 to 20 nm, and C, B, Be and Si are candidates materials as light elements for the multilayer film in this wavelength range. As the wavelength becomes shorter, the reflectance of the multilayer mirrors theoretically decreases, and a system design based on a 13 nm Mo/Si multilayer mirror was considered to be realistic in terms of manufacturing. On the other hand, as regards resist material, the soft X-ray absorption of a polymeric resist increases when the wavelength exceeds 4.5 nm, which is the absorption edge of C, possibly affecting its sensitivity and resolution. Therefore, the sensitivity and resolution of the resist were evaluated in detail using spectral light at three wavelengths of 7, 10, and 13 nm [22], and finally 13nm was selected as the exposure wavelength.

Next, the figure error of a fabricated aspherical mirror, and the wave-front aberration of the optical system after assembly are described. At that time there was no technique for accurately measuring the shape of the aspherical mirror. Even for a spherical mirror, the accuracy of the reference standard of a commercially available interferometer was \( \lambda/10 \) (\( \lambda \) is the 632.8 nm wavelength of He-Ne). Therefore, even in the optical design, we assumed an evaluation with the spherical reference and designed the mirror so that the aspherical ratio was suppressed as much as possible. In an off-axis optical system based on a reflective mask, the incident angle of the mask and the mirror in the optics was designed to have as normal an incidence as possible. To suppress any image shift due to defocusing, the telecentricity on the wafer was taken into account. Thus, the design was completed for a telecentric optical system with a reduction ratio of 1/5 and a resolution of 0.1\( \mu \)m with a numerical aperture (NA) of 0.1 and two aspherical mirrors [23,24]. Based on this system design, we designed and fabricated a two-aspherical-mirror system with an NA of 0.1 [23,24]. Figure 1 shows a schematic of the EUVL system employing a system with two aspherical mirrors.

![Fig. 1. Schematic of EUVL system employing a two-aspherical mirror system.](image-url)
Subsequently, in a joint development with Tinsley Corporation in the United States, we used an interferometer that adopted the aspheric reference using a computer hologram as a measuring machine and achieved a shape precision of 1.8 nm for the first time in the world [25,26].

We have established a method for assembling and adjusting an optical system that measures wavefront aberration using a ZYGO interferometer [27]. Since the optical design is an aspheric off-axis ringfield optical system, the adjustment axis has six degrees of freedom even though there are only two mirrors. In advance, we have devised a method that predicts the wave-front aberration with the assumed assembly error by performing a calculation using an optical simulator, so that the adjustment does not become the local minimum. The final wave-front aberration after assembly was 4.5 nm, and due to the insufficient accuracy of the shape of the aspherical mirrors, Maréchal's criterion was not satisfied. We evaluated the influence of the aspherical mirror processing error on the exposure characteristics using a ray-trace simulation and discussed it in comparison with Maréchal's criterion [28,29]. Furthermore, we proposed a future on-line adjustment system, using the at-wavelength Foucault test, and verified its effectiveness with ray-trace and numerical simulations [30].

An exposure experiment using a two-aspherical-mirror system and a reflective mask was carried out on the beamline BL-1 in the Photon Factory at the National Laboratory for High Energy Physics. The exposure experiment was advanced step by step in parallel with the verification of the manufacturing technology of the aspheric mirror and the establishment of the assembly adjustment technology of the aspherical optical system. Initially, we confirmed the basic operation of the system by using two spherical optical systems [31].

Subsequently, an aspherical optical system with 1/2 the design values was prepared, and the ability to perform aspherical surface processing and an assembly adjustment technique were established [32]. Then, a full size aspherical optical system was made, and exposure experiments were carried out [33]. Finally, due to restrictions as regards the illumination area of the light source, part of the ringfield was illuminated and the transcription of a 0.15 μm L&S pattern was demonstrated in a 2 mm × 0.6 mm region [34-36].

Consequently, we have designed and built a four-mirror grazing incidence, illumination system for EUVL that is applicable to a two-aspherical-mirror system, as shown in Fig. 3 [37] to eliminate the illumination restriction. It was designed as a synchrotron radiation source, and it provides uniform illumination (size: 100 mm × 125 mm) and a proper NA for the object space for incoherent illumination of the imaging optics. It should be noted that these were achieved with a SR source, whose horizontal and vertical divergence differ greatly. A large illumination area was achieved with an oscillating mirror (M3) and synchronous movement of the mask and wafer stages. The rotation of M3 at a constant speed scans the focused spot across the ringfield. This provides not only illumination over a large ringfield, but also improves the uniformity of the illumination even under critical illumination conditions. In accordance with the design, we constructed a beamline for large area exposure demonstration at the synchrotron radiation facility Super-ALIS [38] at NTT Atsugi Research and Development Center.

Figure 4 shows a replicated pattern exposed on an area greater than 10 mm (h) × 12.5 mm (v), which demonstrates the world's first large area exposure of a 10 mm square or more [39,40].

EUVL needs an imaging optical system in the
soft X-ray region where the wavelength is two orders of magnitude shorter than that used for conventional ultraviolet lithography. That means that an extremely high technical hurdle must be overcome, and one by one we presented solutions to these technical challenges namely, the design of two aspherical optical systems and an optical illumination system capable of large area exposure, the processing evaluation of an aspherical mirror, and the establishment of a wave-front aberration measurement method via assembly adjustment.

With the interferometric microscope of this study, an X-ray zooming tube was developed to achieve high resolution magnification.

Next, we describe studies of the exposure characteristics of defects in multilayer masks. These results later triggered the study of mask inspection technology. By using the two-aspherical mirror system mentioned in the previous section, program defects were prepared in a multilayer reflection mask in advance and the exposure characteristics were investigated [43, 44]. This experiment showed that both the defects of the absorber and the phase type defect buried under the multilayer coatings are transferred. The existence of this type of defect, which may not be detected by a particle inspection system using ultraviolet scattering, becomes a big problem as regards reducing the defects of an EUVL mask. To solve this problem, we designed and developed a Mirau type interference microscope to observe the defects directly at-wavelength [45].

Thus, our demonstration that practical large area exposure with EUVL is possible has helped accelerate the subsequent development of EUVL.

4. Application to EUV mask inspection as an interferometric measurement

In this section, we describe the development of a mask inspection system that employs a Mirau type interference microscope with a multilayer film beam splitter [17]. In the early 1990s when EUVL research became full-fledged, there were no imaging devices available in the soft X-ray region. In the hard X-ray region, CCD for visible light could be diverted, but in the soft X-ray region, soft X-rays attenuated with protective oxide film on the surface of the CCD and could not reach the depletion layer. Therefore, we attempted to capture a soft X-ray image with a MOS imaging device (Amplified MOS Imager: AMI) modified for ion beam detection, and succeeded in observing onion cells [41, 42]. An X-ray zooming tube was developed to enlarge the electron image generated from the phosphor screen of CsI with an electrostatic lens.

By installing a multilayer beam splitter, it is possible to obtain contrast even in a phase type defect by interference as shown in Fig. 5. We demonstrated that the program phase defect on the mask can be observed without exposure by using the developed Mirau type interference microscope. In the experiment, we observed natural phase defects buried under the multilayered coatings. These defects were gentle with a step difference of only 6.5nm on the multilayer film surface. This research was transferred through collaboration with Kinoshita of Himeji Institute of Technology from 2002, and various defect observations were made. This work provided the basis for reducing the defects in the mask [46-48].
Fig. 6. Micrographs of native phase defects taken with an EUV Mirau interferometric microscope (left), and a topographic profile measured with an AFM (right).

Regarding mask defect inspection, in 2000, I participated as a visiting scientist at the Lawrence Berkeley National Laboratory in a project investigating defect inspection by soft X-ray scattering measurement. The system uses Kirkpatrick-Baez (KB) optics on the beamline 11.3.2 of an Advanced Light Source (ALS) to form a soft X-ray microbeam with a spot size of 2.5 \(\mu\)m \(\times\) 4 \(\mu\)m. It is a defect detection method that functions by bright-field / dark-field image observation when the soft X-ray microbeam of the exposure wavelength is raster-scanned on a mask blank. In the experiment, the same region of the mask blank was inspected and mapped with a visible particle inspection tool. SEM observation was also employed and the cross correlation of each tool was investigated. The results of correlation experiments on 32 defects showed the possibility of detecting defects of the order of 30 nm in size and also showed the existence of defects of 6nm high and 60 nm in size, which cannot be detected by other inspection methods (Actinic-only defect) [49,50].

The defect of the multilayer mask provided the biggest threat as a possible show-stopper for EUVL. I am convinced that the clarification of issues related to these mask defects and countermeasures have led to the practical application of today's EUVL.

5. Application to thin film analysis as an ellipsometric measurement

This section describes soft X-ray ellipsometry using a transmission type multilayer polarizer. A transmission type multilayer film composed of 50-layer pairs functions was employed as a transmission type polarizer with a 3 digit extinction ratio of when used at a pseudo Brewster angle of 44 degrees. Furthermore, when the incident angle is set at 51.4 degrees according to the phase characteristic of the multilayer polarizer, it functions as a retarder with a relative transmittance of approximately 1 and a phase retardation angle of 90 degrees, which is known as a quarter wave plate.

A soft X-ray ellipsometer was developed equipped with these optical elements [51]. By measuring the elliptical polarization degree of the beamline using this soft X-ray ellipsometer, it was found that the ellipsity angle, \(\tan \epsilon\) was +0.137. It was also possible to freely convert linearly polarized light from a synchrotron radiation source to clockwise or counterclockwise circularly polarized light.

Fig. 7. Schematic view of a soft X-ray ellipsometer.

A soft X-ray ellipsometer was used to evaluate real samples, namely an SOI substrate with an ultrathin superficial Si layer, and the other is a determination of the nature of the interface of multilayer mirrors. In the evaluation of the SOI substrate, the possibility was demonstrated of determining the film thickness with sub-nanometer accuracy on the SOI substrate with a superficial Si layer of 10 nm or less [51].

When determining the nature of the interface of the multilayer mirrors, we compared the validity of the two models that explain the cause of reflectance degradation, namely a model generated by interface diffusion and a model generated by roughness represented by the Debye-Waller factor. From the actual measurement results, it transpired that the model regarded as a diffusion model was more appropriate [52].

As described above, a spectroscopic ellipsometer was realized as a tool capable of investigating the optical constants and thicknesses of thin film materials with extremely high sensitivity in the soft X-ray region.

6. Summary

EUVL is nearing full-fledged practical application to high volume chip manufacturing. This paper describes the establishment of soft X-ray optical technology by multilayer optical elements and the early stages of research into its application as a lithographic technique. In this series of studies,
soft X-ray optical technology was established through the demonstration of three fundamental properties of optics, namely imaging, interference, and polarization in the soft X-ray region, with multilayer optical elements.

As a sophistication of the multilayered film optical elements, we have advanced studies on high reflectance and high heat resistance, which are fundamental performance characteristics as regards reflecting mirrors. Accordingly, it became possible to use a multilayer film as a reflecting mirror satisfying the performance required for EUVL imaging optics. Furthermore, we realized a transmission type multilayer film via stress control and opened up a way of applying the technology to interference and polarization.

We have demonstrated feasibility of an EUVL optical system as a lithographic candidate by establishing a design employing two-aspherical mirror optics, processing aspherical mirrors, assembly technology for imaging optics, and an illumination system for a large exposure area. This result, which shows the possibility of large-area exposure, is epoch-making and greatly promotes the practical application of EUVL.

For interference applications, we realized a multilayer beam splitter, and developed a Mirau interference microscope in the soft X-ray region. By applying this to the defect inspection of a finished EUVL mask, a multilayer film transfer defect including the phase type was detected, and clarified the existence of the defect, which can be detected only at the exposure wavelength.

As regards the application of polarized light, we developed a soft X-ray ellipsometer equipped with transmissive multilayer polarizers as a phase shifter and an analyzer. It was used to evaluate an ultra-thin SOI substrate and understand the nature of the multilayer film interface. It showed the effectiveness of the soft X-ray ellipsometer for ultrathin film evaluation.

In this way, we believe that it became possible to utilize the technology as an optical method in the X-ray region, thus widening the possibility of engineering in this wavelength region, and realizing the practical use of EUVL. Once 13.5 nm EUV is adopted as the lithography wavelength, it will lead to the miniaturization for several generations of lithography technology. Looking back at the history of lithography, the show-stopper is to meet the challenges of material improvement. I hope that further progress in optical technology in the EUV and soft X-ray fields will lead to solutions to the problems posed by these materials.

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This research represents the result of about 10 years of study since I joined a soft X-ray projection lithography group at NTT Laboratories in 1989. The team only ever had seven members at most, Dr. Hiroo Kinoshita, Dr. Hisataka Takenaka, Dr. Kenji Kurihara, Dr. Marcia C. K. Tinone, Mr. Tsutomu Mizota Mr. Nobuyuki Takeuchi, and me.

In the early days of R&D on EUVL, we cooperated with many people to develop technology for future practical use. I would like to thank all the people who worked on EUVL with us.

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