History of extreme ultraviolet lithography

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Extreme ultraviolet lithography (EUVL) technology was proposed and progressed on both hemispheres in the latter part of the 1980s, independently. Although this technology is a design using a catoptric system instead of refraction lens and the accuracy of subnanometer is demanded for all component engineering, the research and development of Japan and the United States has led to significant breakthroughs in processing and measurement technology over the past 20 years. EUVL is now the most promising next-generation technology for large scale integration fabrication. This article discusses the beginnings of EUVL, what advances are needed, and future prospects. © *2005 American Vacuum Society.* [DOI: 10.1116/1.2127950]

I. INTRODUCTION

Soft x-ray reduction lithography using multilayer-coated Schwertzchild optics (SC) was demonstrated[1,2] in 1986. The exposure optics was then refined, and a 0.5 μm pattern was delineated[3] in 1989. However, the next year, the AT&T group demonstrated a diffraction-limited pattern with a size of 0.05 μm.[4] Stimulated by those results, research and development accelerated in both the United States and Japan. The past 20 years have seen many technological advances, and extreme ultraviolet lithography (EUVL) is now the most promising next-generation technology for large scale integration (LSI) fabrication.

In contrast to conventional ultraviolet photolithography, which employs refractive optics, this technology employs an optical system consisting of multilayer-coated mirrors; that is, it is a reflective system. Each aspect of this technology (coating, polishing, metrology, vacuum mechanism, etc.) requires an extremely high precision of less than 1 nm, although nanotechnology seems to have grabbed the world's attention lately. On the road to the achievement of a workable technology, solutions to critical problems in each field must be found, the impact of which will spread widely into other fields. As an example, consider the light source, which is based, for instance, on laser plasma. If a high-intensity light source is realizable, it will lead to improvements in the performance of x-ray microscopes and analytical tools. Progress in optical polishing and shaping will have an impact on the quality of many products. Research on multilayer films promotes the study of the process by which a single atomic layer is formed and also research on the surface interface of materials. Furthermore, the advances in metrology required to make EUVL practical will revolutionize evaluation methods based of the conventional point diffraction interferometer.

Thus, although each technology related to EUVL has a difficult problem that must be solved, this research is part of the process by which we are progressing to the nanoscale regime; and this same process will one day carry us into the picoscale regime. In this sense, the development of EUVL will have a large ripple effect on all fields.

This article discusses the beginnings of EUVL, what advances are needed, and future prospects.

II. EARLY STAGES OF DEVELOPMENT

First, I will explain why I began studying reduction lithography. I was involved in research on x-ray proximity lithography[5] (XPL) around 1983. At that time, the target resolution for XPL was 0.5 μm, which was thought to be difficult to achieve with ultraviolet lithography. We had already developed apparatus for proximity x-ray lithography and examined its applicability to the trial production of devices. We were deeply involved in these trials and in improving evaluation procedures. Our assessment was that the exposure machine and resist performance seemed quite adequate; but we ran into too many problems with the manufacture of proximity masks. It was around that time that I began to seriously consider x-ray reduction lithography as a more viable alternative.

In those days, few researchers were paying much attention to x-ray reduction lithography because a reduction exposure machine using ultraviolet *g*-line light had just appeared on the market. However, the application of reflective optics to x-ray microscopes and x-ray telescopes had been proposed;[6,7] but the key technology, namely, the formation of a multilayer coating, was not advanced enough to be useful. Fortunately, some researchers at my institute who were studying superconducting thin films announced that they had made a multilayer film of tungsten and carbon.[8] This spurred us to immediately launch a project in conjunction with researchers at the Ibaragi Institute to fabricate multilayer films for Schwartzchild-type optics.

Figure 1 shows the configuration of the first experimental setup.[1] In order to ensure a large enough exposure area, the first optical system we designed produced a ring-field exposure area. We used a silicon stencil mask for a transparent mask. Then, we built a system based on the absorption edge of silicon, and started experiments at the High-Energy Physics Lab in Tsukuba. In the beginning, the alignment accuracy

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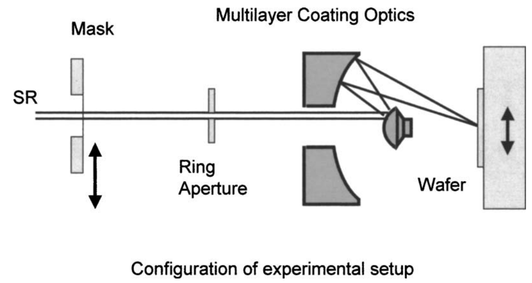

FIG. 1. Configuration of the first soft x-ray reduction system.

of the optics was very poor, and all the patterns we made were severely distorted. We continued a particular set of experiments from one day to the next as long as the alignment remained good enough.

We finally succeeded in fabricating a line-and-space pattern in 1985. This was reported at a meeting of the Japan Society of Applied Physics in the autumn of 1986. However, the response to the announcement was rather negative. People seemed unwilling to believe that we had actually made an image by bending x rays, and they tended to regard the whole thing as a big fish story.

However, my belief remained unshaken that "theoretically, it is possible to produce an image using a reduction optical system consisting of a couple of mirrors coated with multilayer film."

In 1985, Barbee *et al.* reported that they had used multilayer coating to achieve a high reflectivity around a wavelength of 20 nm.[9] That was the first time that a reflectivity close to the theoretical value had ever been obtained experimentally. Since then, Mo/Si multilayer films were deposited on optics, whose films are the most suitable for the wavelength of the Si absorption edge. Moreover, in order to correct the image distortion resulting from the curvature of the mirrors and the pattern degradation due to defocusing, which is needed to enlarge the exposure field, we designed a telecentric two-aspherical-mirror system. In this design,[10] since the curvature radii of these mirrors are almost the same, the Petzval aberrations, which cause the curved image, become zero. This is the principle of the EUVL optics design in Fig. 2.

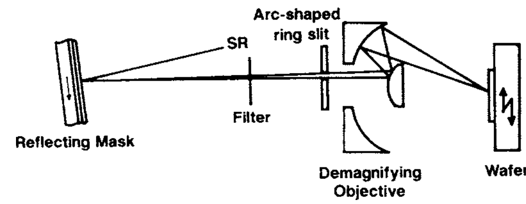

FIG. 3. Schematic illustration of experimental setup using reflecting mask.

An opportunity to announce this development came at EIPB in 1989, where I presented an article entitled "Soft x-ray reduction lithography." That report explained that a SC optical system was used to replicate a 0.5 μm pattern using a reflection-type mask,[3] and based on the target resolution and depth of focus, the required numerical aperture (NA) and wavelength domain were estimated (see Fig. 3).

Moreover, I also made the following suggestions: (1) Since the maximum reflectance of a multilayer film is about 70%, the number of mirrors has to kept as small as possible; (2) based on the arrangement of the mask and wafer, there should be an even number of mirrors; (3) in order to suppress the scattering of light from the mask and to prevent oxidization, the top and bottom layer of the multilayer should be Si; (4) and a multilayer resist coating would be useful for replicating high-aspect-ratio patterns.

At the banquet in the aquarium later, a woman, Dr. Tania Jewell, with a Russian accent cornered me and proceeded to deluge me with questions. The combination of poor Japanese English and poor Russian English made conversation extremely difficult, and our discussion continued for a long time, although Dr. Obert Wood, II of AT&T acted as an interpreter. The next year, AT&T also announced a 0.05 μm pattern. We just remember the discussion that night in Monterey as having been "the dawn of EUVL."

In those days, only three research institutes were investigating EUVL. Dr. A. Hawryluk, Dr. G. Seppala, and Dr. N. Ceglio, who belonged to the x-ray laser group at LLNL and were fabricating x ray optical components, such as FZPs and multilayer films, proposed "soft x-ray projection lithography" using two-mirror optics (shown in Fig. 4) in 1988.[11] Considering contamination, the exposure wavelength was set to the absorption edge of carbon (4.48 nm); and to correct for curvature in the image, a concave spherical mask was

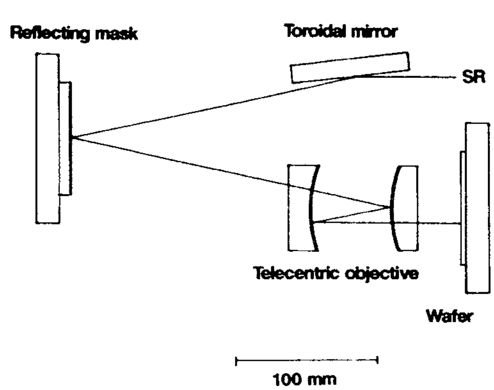

FIG. 2. Principle design of demagnifying optics.

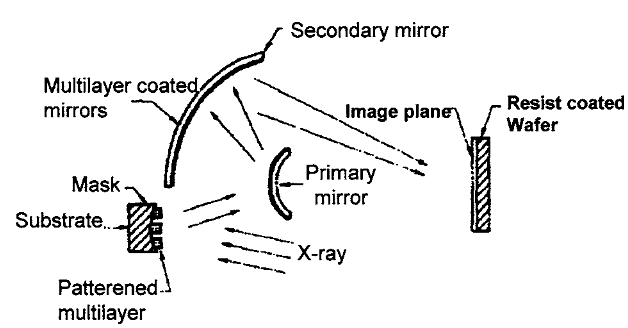

FIG. 4. X-ray reduction camera with corrected field curvature and uniform illumination proposed by LLNL.

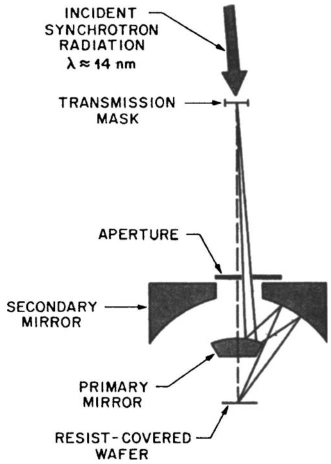

FIG. 5. Schematic diagram of the basic experimental setup by AT&T.

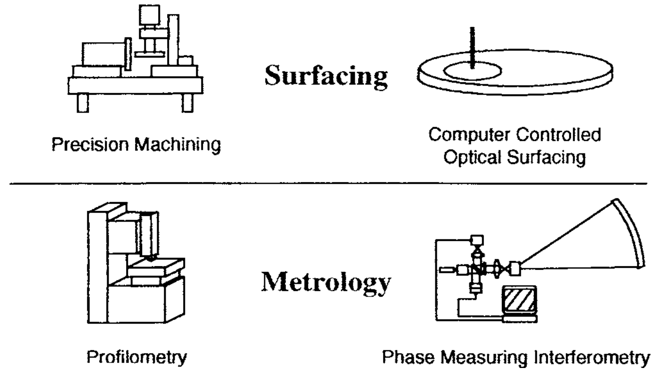

FIG. 6. Aspherical fabrication process with four core technologies by Tinsley.

proposed. Furthermore, they reported that laser-generated plasma was a good source of x rays. In 1989, the wavelength was set to 13 nm, which is what we originally proposed[12] by chance.

Regarding the AT&T group, they have issued many reports on x-ray reduction cameras since 1988. Initially, they aimed at 0.1 μm lithography with a 10 Hz 37.2 nm sodium laser,[13] and they developed two types of optical systems involving the coating of iridium film on a catoptrics system. One was a SC optical system for a wavelength of 36 nm.[14] They used it to demonstrate a 0.2 μm pattern, which was the diffraction-limited performance in 1990. The other was a 1:1 Offner type for a wavelength of 42 nm.[15] They used it to demonstrate a 0.2 μm pattern in 1991. After that, they tried to fabricate a Mo/Si multilayer on SC optics at a wavelength of 14 nm and demonstrated the diffraction-limited performance of 0.05 μm (in Fig. 5) in 1990.[4] Although they specialized in lasers and optical devices, they were also thinking about how to apply laser technology to lithography. Their main goal was to obtain actual proof of the diffraction-limited performance. To achieve it, they employed a reflective system consisting of on-axis SC optics without distortion. That was different from our initial goal of obtaining a large exposure field. Nevertheless, the evidence they obtained regarding the diffraction-limited performance paved the way for the development of reduction lithography.

III. THREE INNOVATIONS THAT ACCELERATED EUVL RESEARCH

Three innovations are key to the development of this technology: Mo/Si multilayer films, and the shaping and metrology of aspherical mirrors.

A. Multilayer film

Multilayer coatings have a long history going back to the 1970s, and considerable progress has been made in this field since then. The first ones were Au/C, ReW/C, and W/C multilayers for wavelengths near the absorption edge of C. They were designed for use in x-ray microscopy, but the reflectivity was not high enough for practical use. It was the research done by Barbee *et al.* in 1985 for a wavelength of around 20 nm and the development of a Mo/Si multilayer that indicated that multilayers might be useful in practical applications.[9]

Many researchers have advanced research on Mo/Si multilayers since the report by Barbee *et al.* in 1985. In Japan, the contributions of Professor Namioka and Professor Yamamoto of Tohoku University and Dr. Takenaka of NTT are especially noteworthy.

B. Fabrication of aspherical mirrors

Around 1990, the highest precision obtainable for an aspherical surface was about 8 nm. At that time, Tinsley furthered the development of the correction optics for the Hubble telescope and raised the bar. This deepened confidence in the mirror-processing capability of the technique they used, namely, computer-controlled surfacing (CCOS).

However, mirrors for a practical exposure system require a precision of 0.5 nm or better. Dan Bajuk and Bob Ahno of the Tinsley Lab, from which I ordered mirrors, thought that level of precision would be unattainable without metrology. They believed that "fabrication is possible if testing is possible."

Figure 6 illustrates their fabrication process for aspherical mirrors.[16] First, precision machining with a diamond grinding wheel produces the initial spherical surface to an accuracy of 1–2 μm, as measured with a contact-type profilometer. Second, an aspherical surface meeting the required specifications is fabricated by CCOS, which employs iterative polishing with substrate polishing tools and a phase-measuring interferometer to measure the shape. The final shape is acquired by repeated polishing and measurement. In 1993, they delivered a couple of aspherical mirrors; but the accuracy was only 1.5 nm for the concave mirror and 1.8 nm for the convex one,[17] and in 1995 we used these mirrors to replicate patterns less than 100 nm in size in an area over 10 mm square by employing a scanning mechanism for the mask and wafer.[18]

However, to fabricate a mirror with an accuracy of better than 1 nm, a metrological method was needed. Figure 7

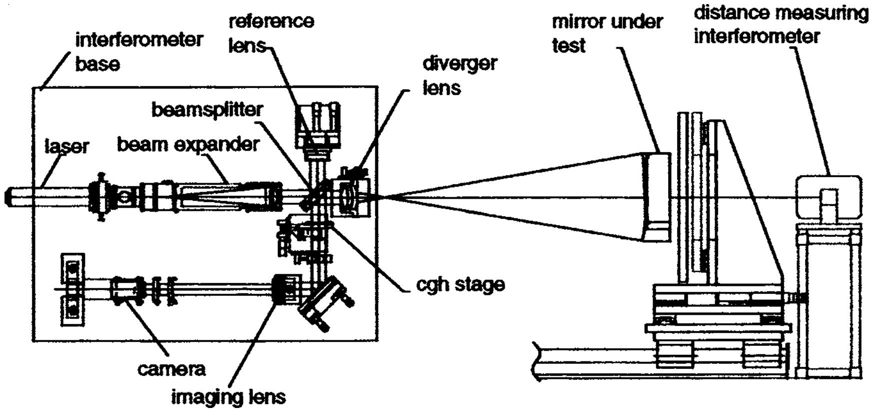

FIG. 7. Twiman–Green interferometer using CGH by Tinsley.

shows a Twaiman green interferometer based on CGH, which applies a Fourier transform to the aspherical surface. CGH calculates interference fringes for actual and ideal wave fronts, and it enabled the precision to reach the required value. That is, this technique of processing the Fourier transform rather than the actual wave front provided an accuracy of 0.5 nm. Further advances in the technology have reduced the roughness in the mid-frequency range, allowing an accuracy of 0.3 nm to be achieved in 2000.

C. Point diffraction interferometer

An interferometer is used to measure the surface figure, and the measurement accuracy depends on the accuracy of the optics in the instrument itself. The need to overcome this limitation engendered the concept of a type of interferometer for which the accuracy of the instrument optics is not a factor determining measurement accuracy. Gary E. Sommargren of LLNL considered the spherical wave emitted from a glass fiber and came up with the idea of determining shape from the interference fringes formed by the wave front reflected from the measurement optics and an ideal spherical wave, taking the uniformity of the diameter of the fiber core into account in Fig. 8.[19] Up to that time, a processed pinhole had been used, which produced a spherical wave that was far from ideal. The system was a technological breakthrough that eliminated spatial restrictions on measurements and provided an accuracy in the subnanometer region.

The wave front aberration of the optical system of our lithography apparatus was designed by this method and a wave front accuracy of 1 nm or less was attained with a four-mirror optical system.

IV. FEATURES OF EUVL TECHNICAL DEVELOPMENT

Initially, the development of EUVL technology in Japan was furthered mainly by NTT; but starting in 1991, Hitachi and Nikon have made advances through experiments at SORTEC and the High-Energy-Physics Laboratory in Tsukuba. In 1993, Professor Namioka organized an annual soft-x-ray optics meeting, which resulted in an intensification of research activities, focusing on multilayers and a light source. After I joined the Himeji Institute of Technology in 1995, Nikon and Hitachi launched joint research projects, resulting in the development of a three-aspherical mirror system. The need for equipment development became widely recognized, and ASET started work in this field in the autumn of 1998. An interesting point is that Intel and Samsung began cooperating with ASET. Until that time, no foreign

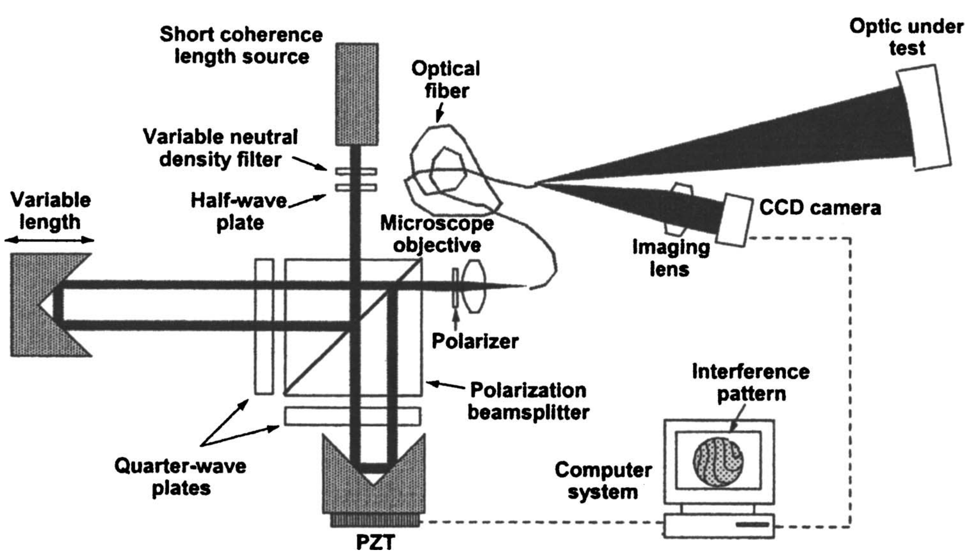

FIG. 8. Schematic of Sommargren interferometer.

company had participated in an ASET program. The entry of Intel and Samsung into EUVL research accelerated the globalization of research and development.

On the other hand, in the United States, the DOE began funding research and development in 1993. Three national research institutes along with AT&T took the lead, and succeeded in developing a 10× system with an optical subsystem consisting of alignment between mask and wafer stages. It has to be remembered that, at that time, the only trial production being carried out to further progress in equipment development was with the 10× system installed at the Sandia National Laboratory. That project lasted for 3 years, and was followed by the establishment of EUV-LLC in 1996–1997. This program contributed to all aspects of technical development until November 2002, and brought the technology close to the stage of practical use. Although no stepper maker participated, many specialists in the fields of optics, polishing, thin films, metrology, and plasma were assembled in a complicated system; and companies such as Intel managed progress. This may have been the first big project in the United States. The technology is now being transferred to United States and European companies, and development toward commercialization is being carried out.

V. PROSPECTS OF COMPONENT ENGINEERING

According to the latest semiconductor road map, EUVL will be introduced for the fabrication of LSIs at the 32 nm node in 2009. To achieve that goal, the trial production of 32 nm LSIs using a beta version of the apparatus must be completed by 2007. Experimental equipment with a NA of 0.3 and an exposure area with a diameter of less than 1 mm is already on the market and exposure tests in cooperation with ISEMATEC, etc. have already begun. This apparatus provides a resolution of 30 nm or less on a resist, and less than 20 nm is possible, considering the performance of the optics. The critical issue right now is the development of a light source that can provide a throughput of 100 wafers/h. Since the specifications of the optical system have already been decided on the development side, the problem is how to boost the intensity of the light source to 115 W from the present 10 W or so. Another issue is the development of a resist with a line-edge roughness (LER) of 3 nm or less, because LER influences the width of an exposed pattern. For resists, there seems to be a tradeoff between LER and sensitivity; and it is important to find a material with a small LER that requires a small exposure dose. If a resist that provides the requisite LER and a sensitivity of 1.0 mJ/cm^2 is developed, the intensity of the light source can be reduced to something like 30 W, which dramatically increases the possibility of the realization of practical EUVL. Unlike a conventional optical system, we have to remember that EUVL is a reflection system, and increasing the number of mirrors is fatal. All the possibilities for the apparatus, light source, and resist must be investigated with the goal of mitigating the severity of the specifications so that a practical EUVL system can be realized as quickly as possible.

VI. CONCLUSIONS

In conclusion, research and development on EUVL over the past 20 years has led to significant breakthroughs in processing and measurement technology. The drive to attain a practical EUVL technology spread to both hemispheres in the latter part of the 1980s; and we can now look back at the history with a wonderful feeling of accomplishment. Many lithographic technologies have been developed and screened during the last 20 years. Although several critical problems still remain with regard to such things as the light source, masks, and resist, it appears now that solutions can be found, since the fabrication of aspherical mirrors and multilayers, which were the biggest headaches, were achieved.

The first international conference with "EUVL" in the title was held near Mt. Fuji in 1993. In the opening address, I said, "As long as we do not lose the desire that has sprung from within us, technology will steadily advance from the micro to the nano to the pico." And now is the time when "pico" can easily be used when talking about optical technology.

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