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A feasibility study on soft X-ray reduction lithography using multilayer mirrors has been performed. An exposure wavelength range of 80 to 110 Å is proposed as the most suitable with current technology considering the optic design, the reflectivity of the multilayer, and the resist characteristics. With the aim of providing multilayers with very sharp interfaces and high reflectivity, we attempted to improve the multilayer fabrication process, with one result being the fabrication of an amorphous Mo/Si multilayer, by controlling substrate temperature. Experimental results of 0.2-μm pattern replication using a multilayer reflection mask are presented.

KEYWORDS: soft X-ray, multilayer, reduction, reflection mask, mirror optics, Mo/Si, synchrotron radiation

§1. Introduction

Advances in multilayer fabrication technology have opened the way to applications[1-9] that employ normal-incidence optics. We have proposed reduction lithography using multilayer mirrors and were the first to demonstrate a demagnified pattern of less than 4 μm using Schwarzschild optics and a stencil mask in a soft X-ray wavelength.* Since then, we have further refined the technology with intent to develop a practical and reliable exposure system for replicating patterns of 0.2 μm or less. By 1989,[7] 0.5-μm patterns were being fabricated with a reflection mask, and in 1991[9] we demonstrated the replication of a 0.15-μm pattern in an area of 0.8 mm × 0.15 mm. These results demonstrate the feasibility of replicating a demagnified pattern using multilayer mirror optics in a soft X-ray wavelength.

This system has the following advantages: 1) a reflection mask with magnified pattern can be used; 2) low distortion can be achieved since a thick Si substrate can be used; and 3) ultrafine patterns of less than 0.05 μm can be replicated.

In order to realize this system, the following problems have to be overcome: 1) design of mirror optics capable of 0.1-μm resolution; 2) fabrication of a multilayer with high reflectivity; and 3) development of high-resolution resist at longer X-ray wavelengths.

This paper describes some of the concepts we have applied to the system and provides some experimental results in order to clarify the feasibility of this system.

§2. System Design

The first problem in the construction of a soft X-ray projection lithography system is selecting the exposure wavelength. The wavelength suitable for a soft X-ray reduction lithography system depends on optic design, multilayer reflectivity and resist characteristics.

We previously reported[7] that an exposure wavelength in the range of 47 to 200 Å is suitable for soft X-ray reduction lithography, where the expected resolution is less than 0.1 μm and the depth of focus is larger than plus or minus 1.0 μm. Exposure wavelengths over the Si absorption edge are especially suitable when considering multilayer reflectivity. However, recent experimental studies on resist[16] and multilayer fabrication have yielded a precise wavelength range.

Figure 1 shows multilayer wavelength dependence. The figure shows the calculated curves for a Ni/C multilayer at around a 50-Å wavelength, a Ru/B_4C multilayer at a 70- to 160-Å wavelength and a Mo/Si multilayer at over a 125-Å wavelength with total film thickness condition equal to 2000 Å and normal incidence. The incident angle is one degree. For a wavelength of over 44.7 Å, we have as yet been unable to develop a multilayer with a high enough reflectivity over 10% for normal incidence, though calculated reflectivity of over 20% has been obtained. This is because it becomes increasingly difficult to control the thickness of the layers and to obtain a con-

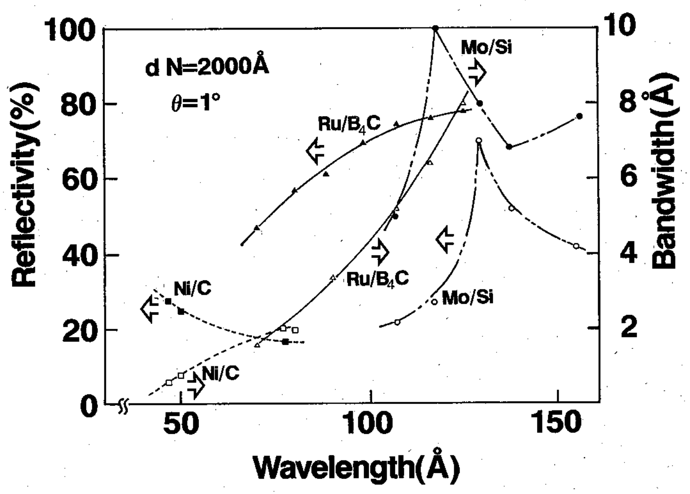


Fig. 1. Calculated reflectivity of Ni/C, Ru/B4C and Mo/Si multilayers.

*H. Kinoshita, T. Kaneko, H. Takei, N. Takeuchi and S. Ishihara: Extended Abstracts of the 47th Autumn meeting of the Japan Society of Applied Physics, Sapporo, September, 1986.

tinuous layer as the layer becomes thinner (<10 Å). On the other hand, in the wavelength region over 70 Å, a calculated reflectivity of over 50% and a bandwidth of over 5 Å are obtained. The measured reflectivity of over 50% is especially easy to obtain at a 130-Å wavelength.

In soft X-ray optics assembled with a few mirrors, reflectivity as well as bandwidth (FWHM) is important in matching a wavelength with peak reflectivity. Therefore, the integrated reflectivity, which is determined by the reflectivity times half a bandwidth, is the more important value for the lithographic tool with a high throughput. Figure 2 shows the integrated effectivity of these multilayers. Assuming that a reflectivity of 30% and a bandwidth of 5 angstroms are the lower limit for obtaining a reasonable throughput, the integrated reflectivity S is over 0.75. This means that at a wavelength of around 50 Å, it seems to be extremely difficult to obtain high enough integrated reflectivity with the current technology. Therefore, an exposure wavelength of over 80 Å has to be chosen.

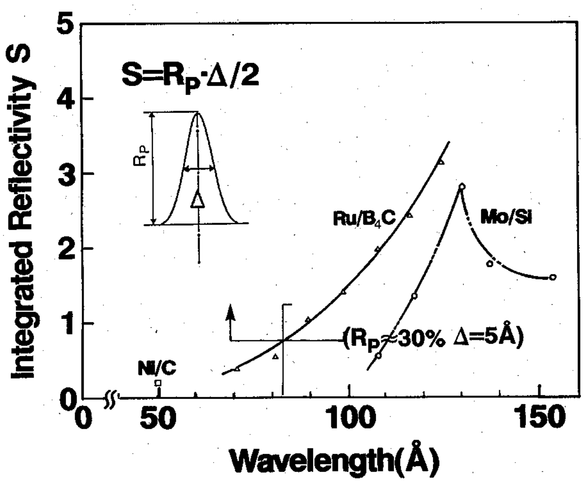


Fig. 2. The integrated reflectivity of Ni/C, Ru/B4C and Mo/Si multilayers.

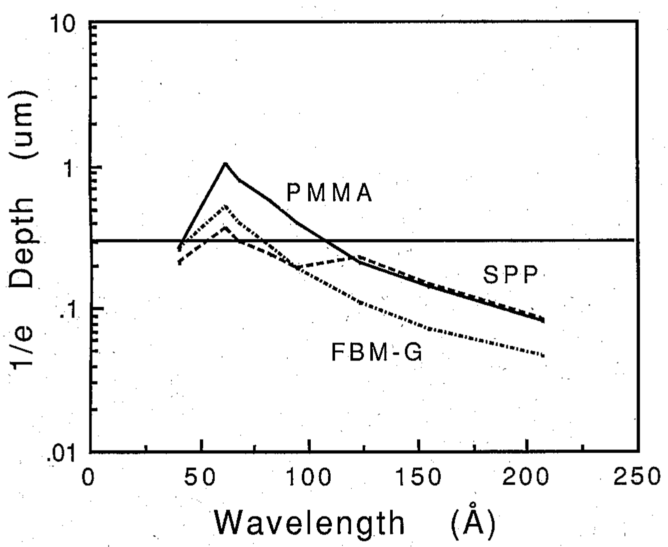


Fig. 3. Calculated exposure depth of several resists.

On the other hand, since the sensitivity and developed depth of the resist depend upon its absorption coefficient for an X-ray, the thickness of each polymer required to give a 1/e attenuation of the incident flux is calculated as a function of wavelength. Figure 3 shows the calculated developed depth of Poly methyl methacrylate (PMMA), Novel silicone-based positive photoresist (SPP) and Poly hexafluorobutyl methacrylate-co-glycidyl metha-crylate (FBM-G). It is observed that the exposure depth at a wavelength of 100 Å is twice that at 130 Å, and at a wavelength of 70 Å, the depth becomes four times the depth at 130 Å. For 130 Å, the greatest depth of penetration of these resists is 0.2 μm for PMMA and SPP. SPP is a negative-type resist containing Si. Resist film thickness with at least three times the minimum feature size will be needed to provide adequate step coverage, a low defect density film and a layer with sufficient resistance to the plasma process. Therefore, for film thickness over 0.3 μm, exposure wavelength shorter than 110 Å has to be selected for the organic resist.

From the above, it is clear that an exposure wavelength from 80 to 110 Å is better for a reduction lithography system.

§3. Optic Design

The second problem is how to construct a demagnifying optical system. To use such a system for the actual fabrication of ultra large scale integrated circuits, a number of serious obstacles regarding the size of the exposure field and throughput must be overcome.

There are two ways to widen the exposure field. One is to design the demagnifying optics to have a large field (>10 mm × 10 mm). During the past few years, a great deal of work has been done on optic design.[10-14] The most common approach is to use full-field optics with 3 or 4 aspherical mirrors. However, as the number of mirrors increases, the throughput goes down, mirror alignment becomes difficult, and the imprecise matching of the wavelength with the Bragg reflection peaks of the mirrors lowers the reflectivity.

The other approach is to use a ring field (>10 mm × 0.2 mm) and a scanning mechanism to synchronize the movements of the wafer and the mask. In this case, two-mirror optics[7] can be used since the area in which aberration must be eliminated is restricted to a thin stripe. Also, the asphericity for two-mirror optics with a ring field is lower than that of four-mirror optics with a large field. The problem here is that the scanning mechanism must be extremely accurate in vacuum.

We have adopted two-mirror optics with a scanning mechanism considering throughput and a large exposure area. Moreover, a practical optical system has been proposed[14] that satisfies 0.1-μm resolution in the area of 15 mm × 0.4 mm. To devise such optics, new aspherical mirror fabrication and evaluation systems with surface figure accuracy of less than 20 Å will be required.

§4. Multilayer Fabrication

Various ways of fabricating multilayers have been studied, including electron beam evaporation, ion beam sputtering deposition, and RF and DC magnetron sputtering. Here, we have employed RF magnetron sputtering deposition because it offers uniform layer pair spacing (< 1% variation) on 4-inch wafers, high reflectivity, repeatability and productivity.

A schematic of the magnetron sputtering system is shown in Fig. 4.[15] Substrates mounted on a rotating table are alternately exposed to individual well-isolated magnetron sources. The individual layer thicknesses are controlled by the deposition rate of the sputtered material, the speed of the rotating table, the source-to-substrate distance, and the interval of the individual shutter left open. Shield masks of a particular shape are placed between the source and the substrates in order to achieve uniform layer thickness. This system offers the flexibility necessary to prepare multilayers having various materials and layer thicknesses.

Evaluation of the multilayer is performed by means of an X-ray diffractometer, a soft X-ray reflectometer and a transmission electron microscope (TEM). The X-ray diffractometer (Cu-Kα) is used to measure the periodicity and the periodic length of the multilayer. According to our experiment, observation from the 1st-to 5th-order Bragg's peak is needed to confirm the periodicity. The soft X-ray reflectometer is used to measure soft X-ray reflectivity at the wavelength and the angle of incidence. Interfacial characteristics, especially the growth of the intermediate layer, are observed by TEM.

Figure 5 shows the measured S-polarization reflectivity of the Mo/Si multilayer as a function of wavelength. The d spacing of this multilayer was 67.1 Å; incident angle was 15 degrees; and layer number was 30 pairs. We have obtained a peak reflectivity of 51%, but the calculated value is 72.4%. The interface roughness of this multilayer was estimated to be about 9 Å by the Debye-Waller factor. Although a Mo/Si multilayer reflectivity of over 50% at wavelengths greater than 124 Å is obtained, cross-sectional TEM images reveal that the interfaces of Mo/Si multilayers are not well defined due to a composite layer that results from mixing the two elements. In addition, the Mo partially crystallizes into grains that can be as large as the thickness of the Mo layer itself. This imperfect layer apparently causes some degradation of the image quality and the drop in the reflectivity.

We tried a number of approaches[15] to solve this problem, and found that the quality of the Mo/Si multilayer depends to a large degree on the process condition. Figure 6 shows TEM photographs of a cross section.

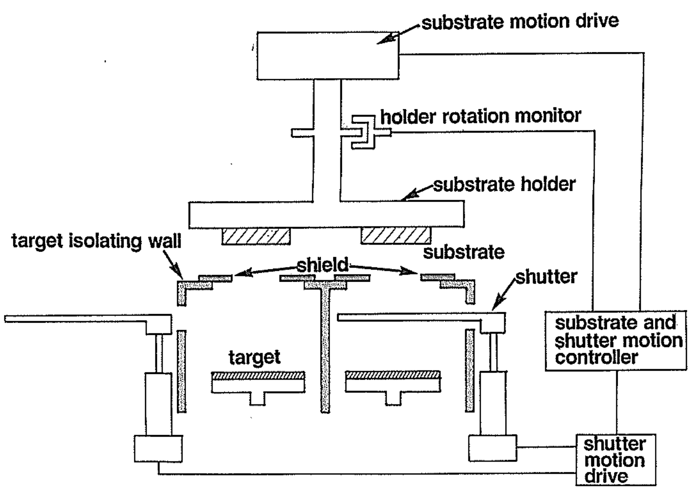


Fig. 4. Schematic illustration of the RF magnetron sputtering system.

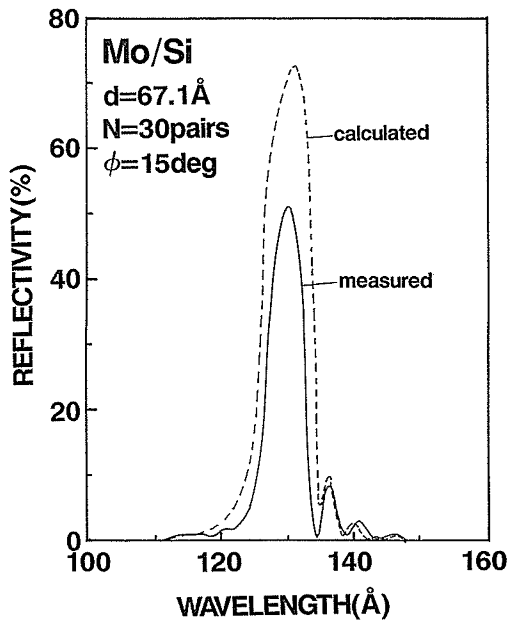
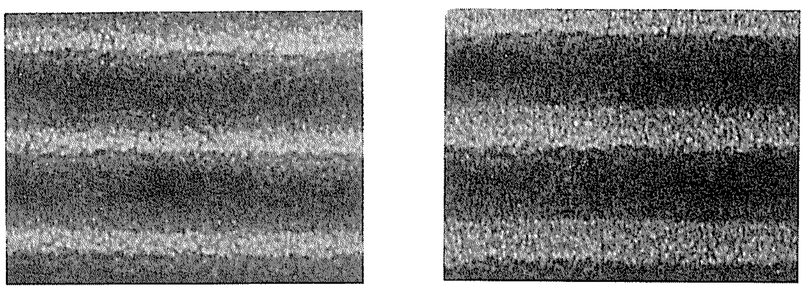


Fig. 5. The measured reflectivity of Mo/Si multilayer.



(a) (b)

Fig. 6. Cross-Sectional TEM photograph of Mo/Si multilayer.

Figure 6(a) shows the condition of the deposition after heating of the substrate, and Fig. 6(b) shows it in the case without heating. It can be seen that the interfaces of (b) multilayer are very sharp and well defined and that the interface roughness is very small. We have succeeded in obtaining an amorphous molybdenum by controlling the substrate temperature.

§5. Experimental

Figure 7 shows the experimental configuration used to test the feasibility of reduction lithography using a reflection mask.

The system consists of a synchrotron radiation source, a carbon filter to cut out long wavelengths over about 400 Å, a reflection mask, ring slit, 2 spherical mirrors for the demagnifying optics, and a wafer. Movements of the mask table and wafer table are synchronized to widen the exposure field.

The incident angle of the SR beam is critical, which means that the beam must be aligned very precisely with the mask. For this reason, all components are mounted on a rotating stage. The image field is about 0.8 mm × 0.15 mm in size, and the demagnification is 1/8.

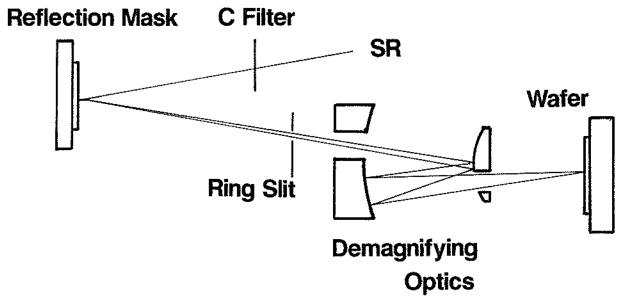


Fig. 7. Schematic illustration of the experimental setup to evaluate the image-forming characteristics.

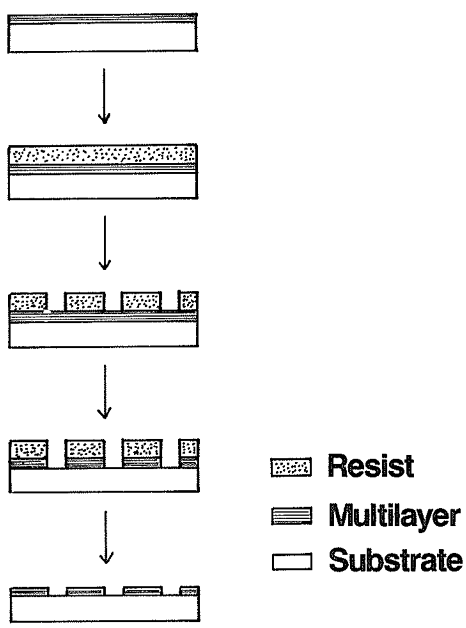


Fig. 8. Procedure of a multilayer reflection mask fabrication.

The curvature of the convex mirror is 45 mm, and that of the concave mirror is 18 mm. These mirrors are spherical. The numerical aperture is 0.1.

The mirrors are made of Mo/Si multilayer deposited by RF magnetron sputtering on spherical substrate with an rms surface roughness of 1.2 Å measured by surface profiler (ZYGO).

The process for fabricating a reflection mask is shown in Fig. 8. The reflection mask is a key component of the system, and must provide high contrast, high reflectivity, broad bandwidth, and homogeneous reflectivity all across a 4-inch wafer. First, the multilayer is deposited on a super smooth silicon or silicon carbide substrate. Then the resist is coated and the expected pattern is exposed with electron beam or photolithography, and developed. Finally, the patterns are dry-etched into the multilayer, and the resist is removed.

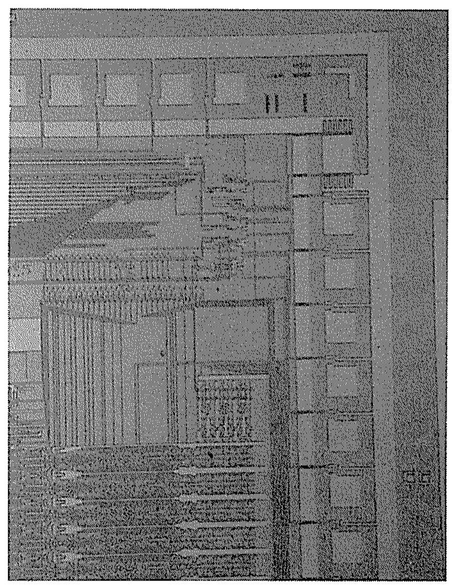


Fig. 9. Photograph of a reflection mask pattern.

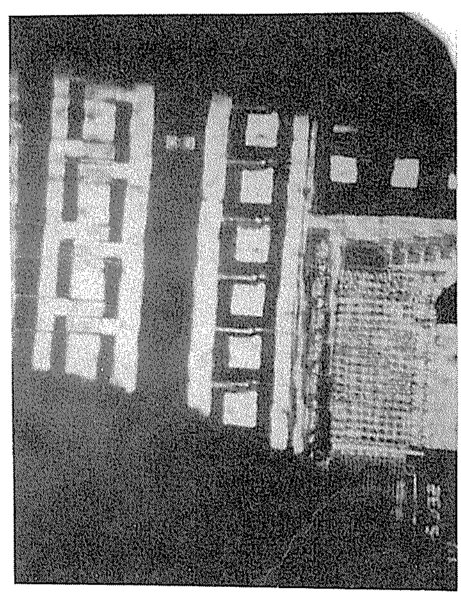


Fig. 10. Whole image of a ring stripe field.

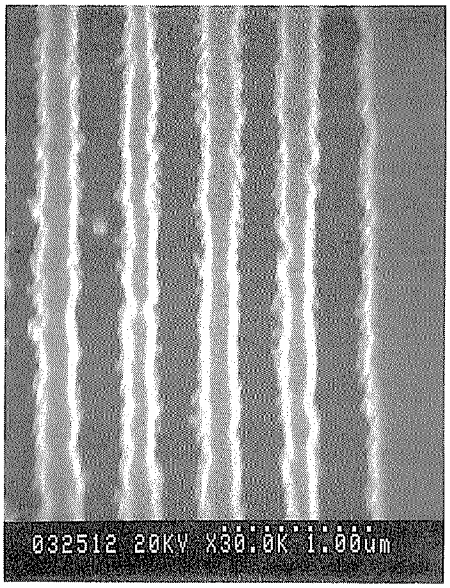


Fig. 11. SEM photographs of 0.2-μm line-and-space pattern obtained using the trilayer resist.

The advantages of this process are that the surface of the multilayer is not roughened by the etching process, and the width of the patterns does not change when the patterns are transferred to the multilayer.

A photograph of a reflection mask is shown in Fig. 9. The original patterns have a minimum feature size of 1 μm. Sulfur hexafluoride gas was used as the etchant for the Mo/Si multilayer. It is applied to the entire 4-inch wafer and exhibits uniform quality throughout.

The whole image of a ring field for an LSI pattern is shown in Fig. 10. The exposure area was 0.8 mm × 0.15 mm and the magnification was 1/8. The patterns have a little irregularity owing to surface figure error, which has to be improved.

The pattern in Fig. 11 was replicated in a trilayer resist system consisting of FBM resist, amorphous Si, and AZ resist (OFPR). Thicknesses of the layers were 0.05 μm, 0.01 μm, and 0.45 μm, respectively. The replicated pattern is a 0.2-μm line-and-space pattern. The irregularity along the edge is observed because of the very thin film.

§6. Conclusions

A soft X-ray reduction lithography system using multilayer mirrors has been developed. We proposed that the most suitable exposure wavelength is from 80 to 110 Å. To obtain a high throughput and a large exposure area, a reduction system consisting of two-mirror optics and a reflection mask with a scanning mechanism was adopted. A full 4-inch wafer reflection mask with high contrast and uniform quality throughout was fabricated using the new process. The structure of the Mo/Si multilayer was refined to achieve smooth interfaces between the multilayers and a high reflectivity of over 50%. Fine patterns of less than 0.2 μm at a demagnification of 1/8 were obtained with a reflection mask in the area of 0.8 mm × 0.15 mm.

The next step is to fabricate a practical optical system and use it to expose demagnified patterns with 0.1-μm resolution in a large square field.

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