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Silicon nitride zoneplates and packaging for extreme ultraviolet instruments

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Diffractive optical elements such as Fresnel zoneplate lenses have many uses at extreme ultraviolet (EUV), particularly in short focal length, high-resolution applications. However, the diffraction efficiency of a pure absorption zoneplate is limited to about 10%, and it suffers additional loss through the membrane support material. To this end, the authors explored the possibility of silicon nitride (Si_3N_4) as a EUV phase shifting material. At an etched depth of 244 nm, they measured a diffraction efficiency of 18% in the first order and 18% in the zero order, which compares favorably to an amplitude grating of 10% and 25%, respectively. The measured efficiency as a function of etch depth matches the scalar theory quite well using a measured EUV index of refraction $0.9790 + 0.0066i$ at the wavelength of 13.5 nm. To further increase the efficiency, zoneplates were made freestanding, with the support membrane completely removed, and a 15% absolute efficiency was obtained. Vector electromagnetic calculations showed that at normal incidence, these optics produce excellent wavefront and efficiency for outer zones of 50 nm or larger. Zoneplates of narrower zones or those illuminated obliquely can suffer larger wavefront errors and low efficiency and would require careful design optimization. In the work, the authors also demonstrated a technique to package zoneplates and associated apertures for high precision insertion and removal from a EUV instrument. This technique has yielded alignment accuracy from a few microns to few 10s microns, depending on the exact design.

I. INTRODUCTION

Diffractive optic lenses such as Fresnel zoneplates have some unique advantages over reflective optics. These lenses can be made in a planer process and have high resolution, short focal length, and be arranged in arrays for interchange or parallel processing. Inspection tools such as the AIT[1] and SHARP[2] use zoneplate lenses to produce a highly magnified image of a extreme ultraviolet (EUV) mask. Scanning probe instruments can also be made using zone- plate optics. Diffractive optical elements can be made with several orders of magnitude less mass than reflective optics, therefore allowing incorporation into mechanical structures with stiff, high-resonance frequencies. Unfortunately, EUV diffractive optics are limited in efficiency, compared to reflective EUV optics. For a pure amplitude square-wave diffractive element, in which the transmitted beam is either completely absorbed or fully transmitted, the diffraction efficiency is about 10% (or $1/\mathrm{p}^2$). This number can increase for a phase shifting absorber up to 40%, when the optics purely phase shift and do not attenuate light. Real materials are between these two limits. In comparison, at EUV wavelengths, high throughput multilayer coatings with reflectivity approaching 70% (Ref. 3) are available. A two bounce optic, such as a Schwarzschild objective, would have an efficiency approaching 50%. Therefore, finding a suitable material for efficient zoneplate optics is important to compete with reflective optics and maintain high system throughput.

Among numerous materials, molybdenum has good refractive index in relation to its absorption.[4] Molybdenum gratings, which could theoretically deliver more than 30% diffraction efficiency, have been reported.[5,6] However, fabrication of low stress Mo films and gratings with straight side- walls and smooth lines at sub-100 nm dimension is still challenging. In this work, silicon nitride, Si_3N_4, which has been used as the membrane material for soft x-ray materials for many years,[7] was chosen. It is strong and commercially available for different thicknesses and amount of stress. Processes for wet and dry etching[8] as well as cleaning are well established. The material is also environmentally stable and can be patterned relatively easily. In this paper, the authors explored the potential of Si_3N_4 as a EUV phase material and achieved efficiency improvement using the material.

II. EXPERIMENTAL Si_3N_4 RESULTS

To investigate the suitability of Si_3N_4 as a phase shifting material for efficient EUV optics, we first measured the index of refraction. Figure 1 shows the measured reflectivity of a sample with approximately 100 nm of Si_3N_4 on a Si wafer. The reflectivity curve covers the range from near glancing incidence to near normal incidence and the reflectivity spans four orders of magnitude. From this data, both the index of refraction, n, and the thickness can be determined. The best fit shows an index of refraction of 0.979 + 0.0066i and a thickness of 102 nm. Based on this index of refraction, Si_3N_4 should be a good candidate for making efficient EUV zoneplate optics. Figure 2 shows the complex amplitude of a wave

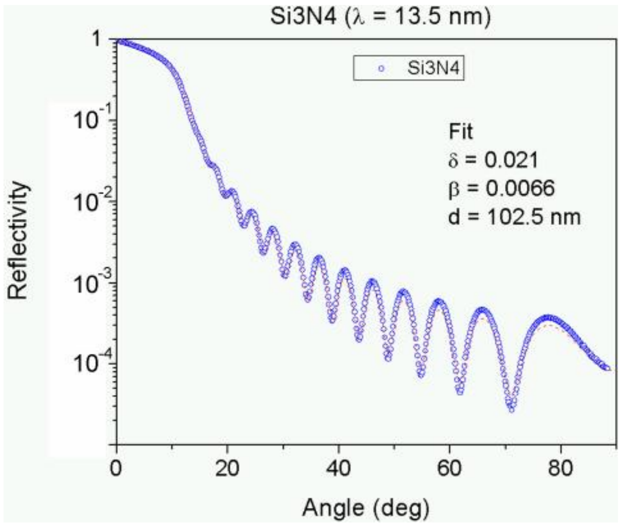

FIG. 1. (Color online) Reflectivity as a function of angle of a Si_3N_4 on Si sample covering several orders of magnitude from glancing incidence to near normal incidence. The best fit parameters show n = 0.979 + 0.0066 i and thickness = 102.5 nm at a wavelength of 13.5 nm.

transmitted through different thickness of Si_3N_4 compared to free space. The square of the magnitude of the vector from (1 + 0 i) to a point of this curve is proportional to the diffraction efficiency of a grating or a zoneplate predicated by the scalar theory.

To demonstrate the diffraction enhancement of Si_3N_4 for diffractive optics, we fabricated a series of gratings in 400 nm thick Si_3N_4 membrane. The gratings had a period of 600 nm. By etching the membrane for different times, we were able to generate gratings from 92 nm to 327 nm deep. SEM micrographs showed the linewidth to period ratio, b, to be 0.56. Figure 3 and Table I show the experimental diffraction measurements. The solid lines represent a scalar diffraction calculation based on the measured values of the line to period ratio, thickness, and index of refraction. The best grating, with a depth of 244 nm, shows a diffraction efficiency of 18% in the first order and 18% in the zero order, which

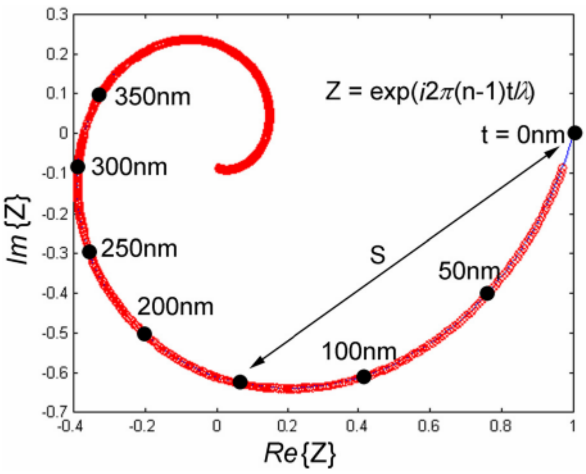

FIG. 2. (Color online) Complex amplitude Z of a wave propagated through a thickness, t, of Si_3N_4 compared to a wave propagated through free space. The scalar diffraction efficiency of the mth order is equal to $(S/(mp))^2$ sin(mpb), where S is the square of the length of vector.

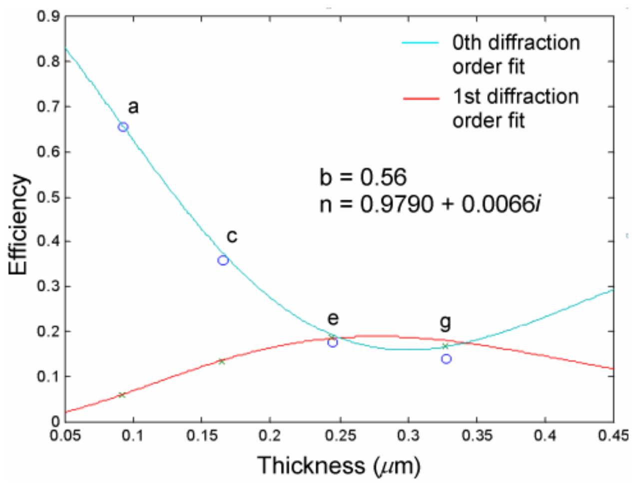

FIG. 3. (Color online) Measured zero order and first order diffraction efficiency of a 600 nm period grating with a line to period ratio, b, of 0.56. The solid lines represent the scalar theory efficiency and agree well with the measurements.

compares favorably with 10% and 25% for an amplitude only zoneplate. To the authors' best knowledge, these are the first measurements of silicon nitride structures as EUV optics.

To improve the overall efficiency of Si_3N_4 zoneplates, the support Si_3N_4 membrane should be made as thin as possible. Here, zoneplates were made "freestanding" with the individual zones held together by thin "buttresses." For this design, it is important that the silicon nitride has low tensile stress to maintain the flatness of the membrane structures. Figure 4 shows a "freestanding" structure with a period of 160 nm and linewidth of about 80 nm, which resulted in 15% absolute efficiency. The buttress size and density were minimized to balance the robustness of the structure and EUV absorption by the buttresses. Figure 5 shows an array of freestanding zoneplates used for mask inspection. While the buttresses were placed quite uniformly to achieve best mechanical stability, no impact on imaging such as scattering has not been observed.

While the optics here were fabricated entirely out of Si_3N_4, the diffractive structures could be made on top of other membrane, particularly of high transmission at EUV.

TABLE I. Measured diffraction efficiency for 600 nm period gratings of various depths in 400 nm thick silicon nitride membrane at 13.5 nm wavelength.

	Silicon nitride grating depths (nm)			
Diffraction order	92	165	244	327
-4	0.0006	0.0018	0.0034	0.0051
-3	0.0046	0.0106	0.0147	0.0120
-2	0.0006	0.0020	0.0044	0.0078
-1	0.0608	0.1327	0.1812	0.1584
0	0.6584	0.3614	0.1794	0.1238
1	0.0596	0.1347	0.1875	0.1589
2	0.0008	0.0019	0.0040	0.0077
3	0.0046	0.0110	0.0157	0.0123
4	0.0008	0.0018	0.0033	0.0054

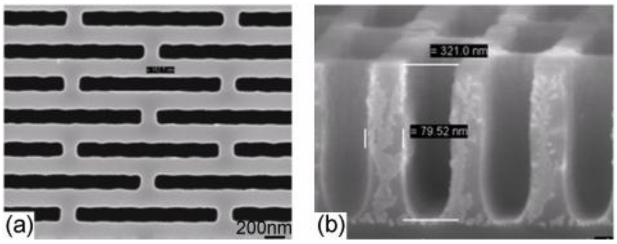

FIG. 4. (a) Top and (b) cross section view of a “freestanding” Si_3N_4 structure held together with buttresses etched all the way through the Si_3N_4 membrane. The period is 160nm and the thickness is 320nm. The measured absolute diffraction efficiency of this structure is 15%, which is less than an ideal structure due to the finite width of the buttresses.

One good candidate is low stress silicon membrane, which can be made to be robust and flat, and has transmission larger than 80%.[9] With a full support membrane, the Si_3N_4 structure would be mechanically stronger than the freestanding counterpart.

III. SIMULATION OF Si_3N_4 DIFFRACTIVE STRUCTURES

Theoretical calculations were performed to understand the performance of using Si_3N_4 diffractive optics for high resolution applications. An internally developed full vector solutions to Maxwell’s equations[10] similar to the Gsolver software was used. Figure 6 shows the efficiency and relative phase error dependence (normalized to 2p) of the first diffraction

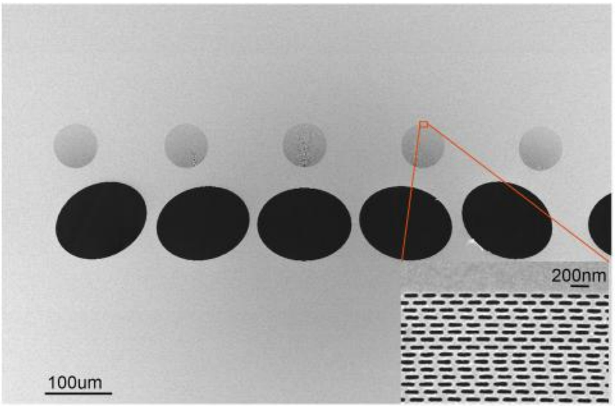

FIG. 5. (Color online) Freestanding zoneplate array in 100nm thick Si_3N_4 used for EUV mask inspection.

order on the grating period for normal incidence. Silicon nitride of 250 nm thickness was assumed. For periods above 100 nm, the efficiency response is relatively flat and zoneplates with a resolution or zonewidth larger than 50 nm should perform well. Below this, the responses degrade rapidly. The electromagnetic effects at the small periods are more pronounced in mask measurement at a fixed angle like in the SHARP setup. For a grating with a 6° incident angle, the efficiency and relative phase error deteriorate for periods

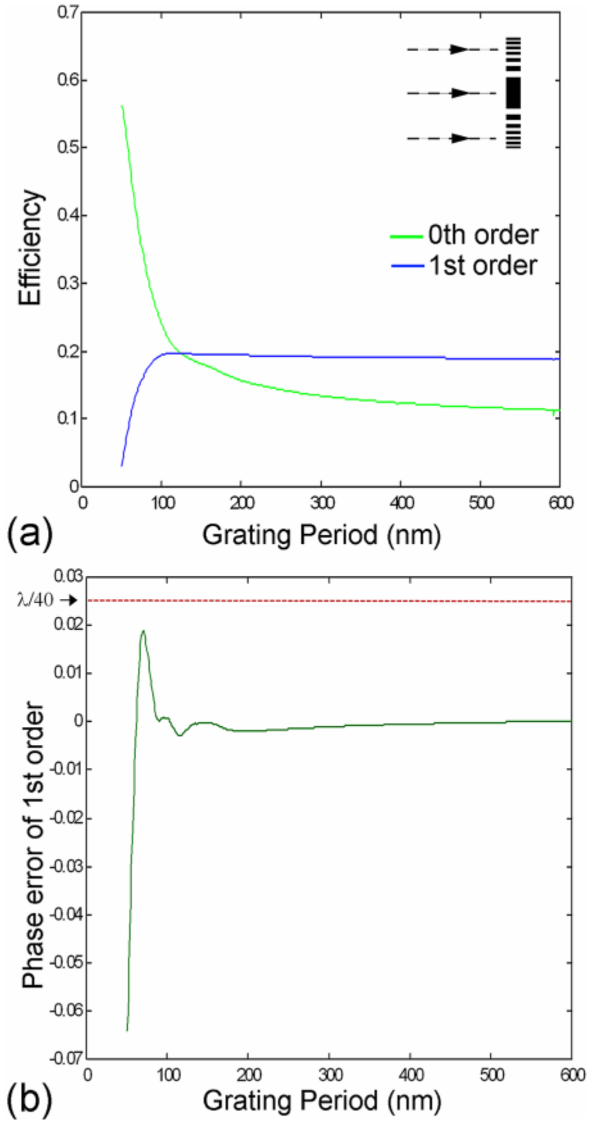

FIG. 6. (Color online) (a) Electromagnetic calculations of the efficiency and (b) phase error normalized to 2p, of the first diffracted order as a function of period at normal incidence. A Si_3N_4 thickness of 250 nm was assumed. 1/40 represents an acceptable relative phase error. The responses are flat until a period of about 100 nm at which point it rapidly changes. Zoneplates with outer zones of 50 nm or larger should perform as expected. Zoneplates with smaller outer zones may have additional aberrations due to the high-aspect ratio waveguide nature of the zones.

smaller than 160nm (Fig. 7). We do not believe Mo and Ru, which have the optimal phase shifting thickness around 86 nm and 55 nm, respectively, suffer such small-period degradation. However, these calculations at one fixed thickness do not reflect the limitations of Si_3N_4 EUV optics. Optimization of the grating thickness and/or linewidth for each period would improve efficiency, and the zone radii may be determined to optimally control phase.

IV. MECHANICAL PACKAGING WITH BALLS AND GROOVES

Diffractive optics need to be incorporated into complete optical and mechanical systems. It is ideal that the mechanical interface will result in reproducible and accurate placement. A typical EUV application involves coupling of a zoneplate to an aperture, which has to be aligned within a few microns in all three dimensions, as well as to the rest of the system. To this end, we have exploited the kinematic

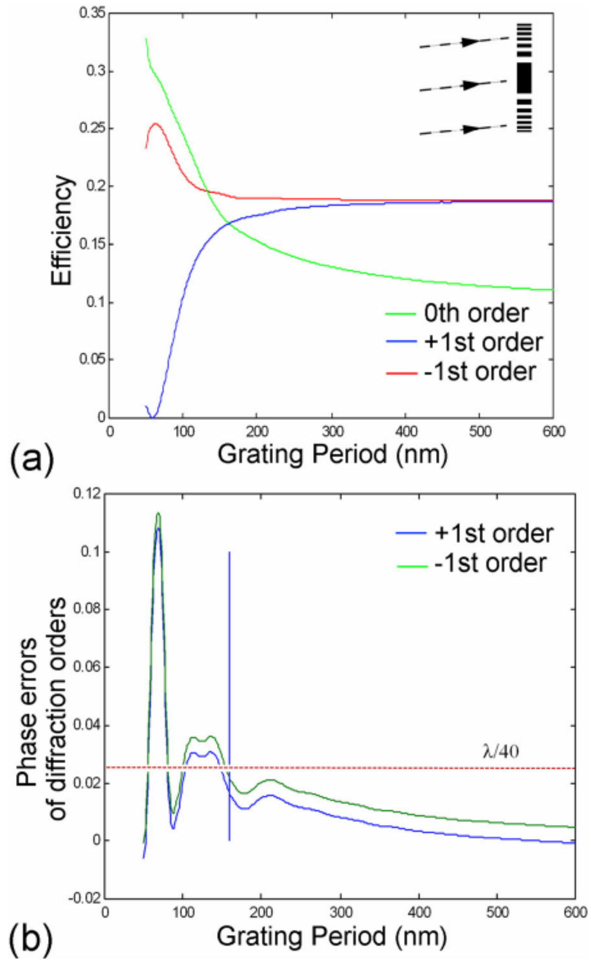

FIG. 7. (Color online) (a) Electromagnetic calculations of the efficiency and (b) phase errors normalized to 2p, of the different diffracted order as a function of period, with a 6° of incident angle. A Si_3N_4 thickness of 250 nm was assumed. k/40 represents an acceptable relative phase error. The efficiency is flat until a period of about 160nm at which point it rapidly changes. Zoneplates with outer zones of 80 nm or larger should perform as expected. Zoneplates with smaller outer zones may have additional aberrations due to the high-aspect ratio waveguide

nature of the zones.

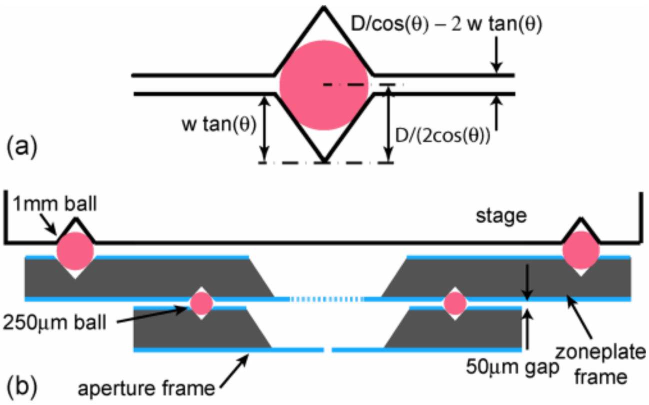

FIG. 8. (Color online) (a) Precise gap is determined by the ruby ball diameter and the lithographically defined grooves. w is the half width of the groove, D the diameter of the ball, and h equals to 54.7° defined by the silicon crystal planes. (b) This concept is used to attach an aperture and mate to the stage.

approach using balls and grooves to produce a robust, accurate package. The grooves are etched in the zoneplate and aperture silicon frames using anisotropic potassium hydroxide etching. The angle is 54.7°, and the placement is done in the lithography steps so that the registration of the zoneplate features and the grooves can be made to submicron tolerances. We used ruby balls of diameters between 250 Im and 1 mm, which are commercially available with tight tolerances and reasonably priced. The balls are secured in the grooves using a low viscosity epoxy manually applied under a stereo microscope. Typical errors are in the few micron range for the smaller balls and the 10 Im range for the larger balls. Figure 8 shows the concept, and Fig. 9 shows a packaged zoneplate with an attached aperture. Repeatability of placing and replacing a package of about a micron has been achieved, and package accuracy, the absolute placement of the aperture and zoneplate, of about 5 Im has been achieved.

V. SUMMARYAND CONCLUSIONS

Diffractive optics such as zoneplates are useful in EUV instruments due to a combination of characteristics such as short focal length, planar nature, low mass, and the ability to make arrays, despite the fact that they do not compare favorably in terms of efficiency to multilayer coated

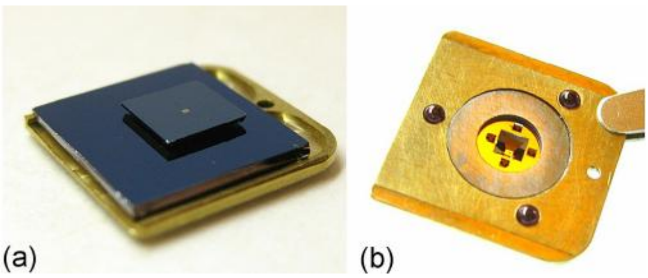

FIG. 9. (Color online) (a) Front side and (b) backside of a packaged EUV zoneplate and aperture pair. The package was glued to a metal plate with through holes for ease of handling.

reflective optics. Silicon nitride, a common x-ray membrane material with well established nanofabrication processes, was investigated as a phase shifting, efficiency enhancing material. For the first time, 18% first order diffraction was obtained at a thickness of 244 nm, which was in close agreement with the scalar theory. However, full vector electromagnetic calculations showed decreasing performance at about 50 nm resolution in normal incidence and 80 nm at 6° incidence. Further studies to understand the effects of parameters such as Si_3N_4 thickness, duty cycle, and zone placement are warranted to optimize zoneplates of higher resolution or for specific optical setup. In this paper, freestanding, buttressed zoneplate structures were developed to eliminate membrane absorption for higher overall efficiency. Packaging using kinematic configurations with balls in lithographically defined grooves has been also demonstrated as a means for incorporating zoneplates into EUV instruments with repeatable positioning and absolute accurate assembly.

ACKNOWLEDGMENTS

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