EUV Transmission Lens Design and Manufacturing Method

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Abstract

This paper outlines a design for an EUV transmission lens comprising blazed, phase-Fresnel structures approximated by a stepped profile. The structures can be formed on both sides of a thin silicon substrate, providing many more phase levels than would be possible with one-sided lenses. An e-beam fabrication technique with nanometer-scale patterning accuracy is outlined.

Lens Design

EUV transmission lenses have utility for microscopy applications such as actinic inspection and metrology in semiconductor manufacture [1, 2]. Typically, the lenses are zone-plate elements comprising annular zones with a rectangular zone profile (Fig. 1). The zones preferably comprise transparent, phase-shifting rings (e.g. molybdenum rings on a silicon substrate) for optimum diffraction efficiency.

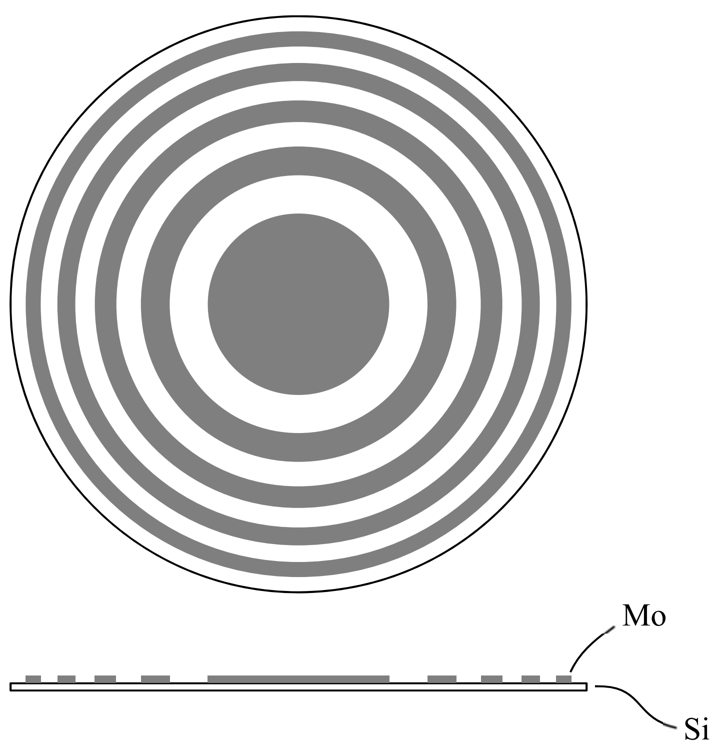

Figure 1. Plan view and cross-section of a zone-plate lens, which has a rectangular zone profile.

Higher diffraction efficiency can be achieved by using an asymmetric blazed profile, which is optimized to concentrate transmitted light in a first diffraction order. A phase-Fresnel lens with sawtooth-profile zones (Fig. 2) can theoretically concentrate all of the transmitted light in the first order (within the approximations of Fourier optics). For a molybdenum grating operating at wavelength 13.5 nm, a sawtooth profile with 177-nm depth would achieve 60% efficiency in the first order (neglecting substrate losses). The efficiency is less than 100% due to optical absorption in the molybdenum, which can be reduced by slightly thinning the profile. A uniform thickness reduction of 27 nm would increase the first-order efficiency to 66%, although this would also increase the efficiency in other diffraction orders, which could be a concern for stray light control.

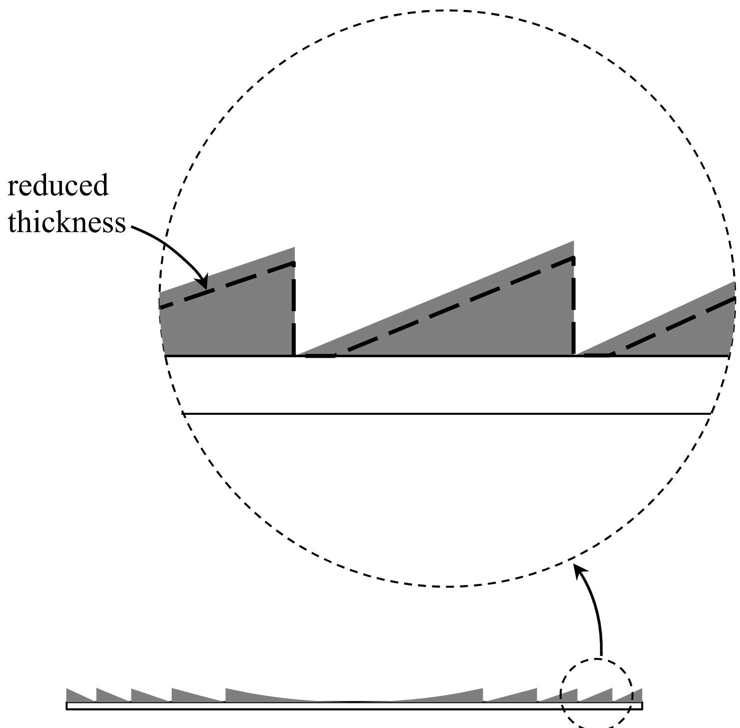

Figure 2. Cross-section of a sawtooth-profile phase-Fresnel lens (standard and thickness-reduced).

A sawtooth profile shape cannot be easily manufactured but can be approximated by a stepped profile (Fig. 3), which can be formed with standard lithography processes. The four-level (three-layer) structure illustrated in Fig. 3 is optically equivalent to a phase-Fresnel lens blazed for the first order, in series with a quarter-period phase-Fresnel lens, which diverts some energy into diffraction orders 1+4*m* for integers *m* (Fig. 4). The high-order scattering can be reduced by using more layers, at the cost of more process complexity.

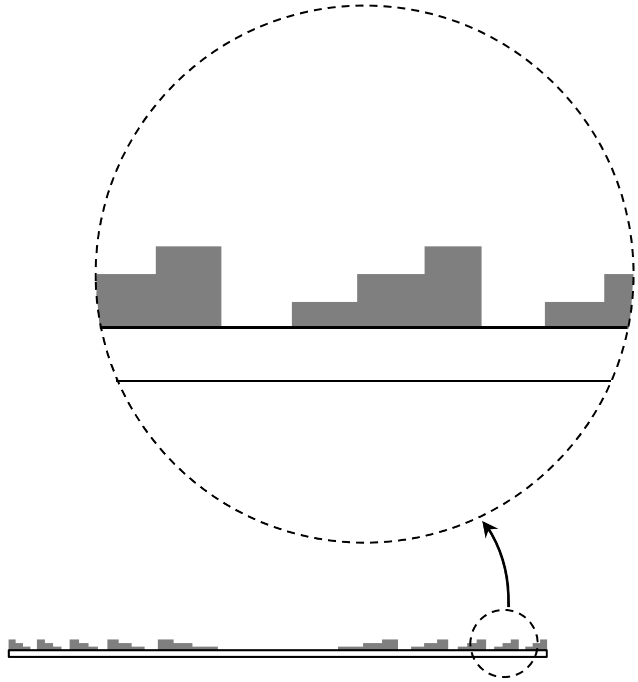

Figure 3. Cross-section of a stepped, 4-level phase-Fresnel lens.

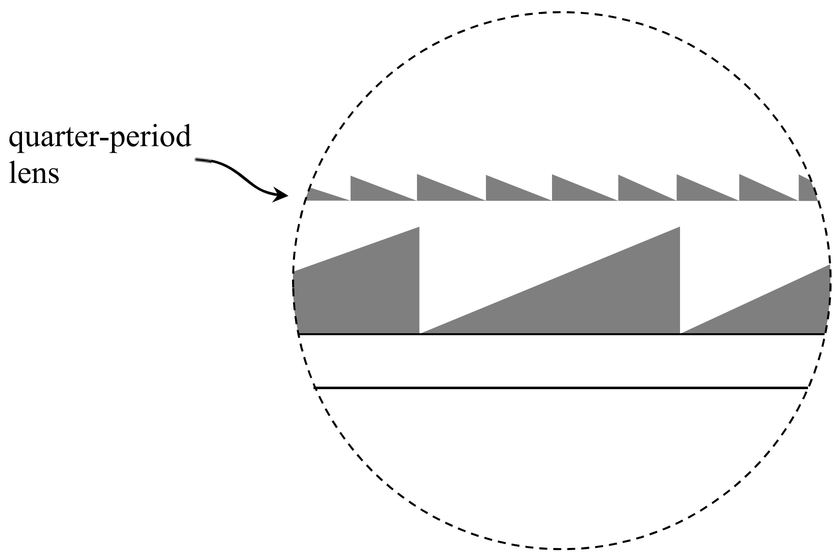

Figure 4. Two stacked phase-Fresnel lenses, equivalent to the stepped-profile lens of Fig. 3.

An alternative lens structure, which is substantially equivalent to the 4-level structure in Fig. 3, consists of two zone-plate lenses formed on both sides of a thin substrate, Fig. 5 [3]. The lens has only two patterned layers, but it is optically equivalent to the three-layer structure in Fig. 3.

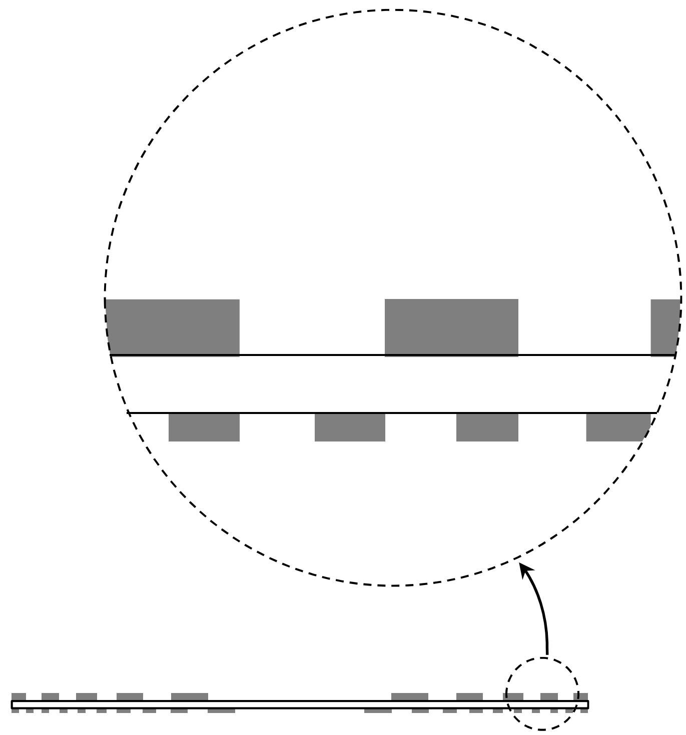

Figure 5. Double-sided EUV lens with zone-plate structures on both sides.

More layers can be used to increase optical efficiency in the first diffraction order and to minimize stray light in extraneous orders. For example, Fig. 6 illustrates a double-sided lens with 3 layers on each side, which is equivalent to the 15-layer structure in Fig. 7. In general, a double-sided lens with M surface levels (M-1 layers) on one side and N levels (N-1 layers) on the other side is substantially equivalent to a one-sided lens with M*N levels (M*N-1 layers).

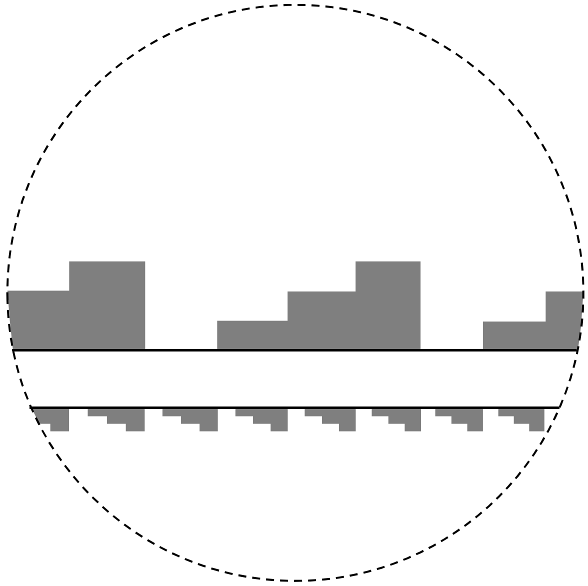

Figure 6. Double-sided EUV lens with 3 layers on each side.

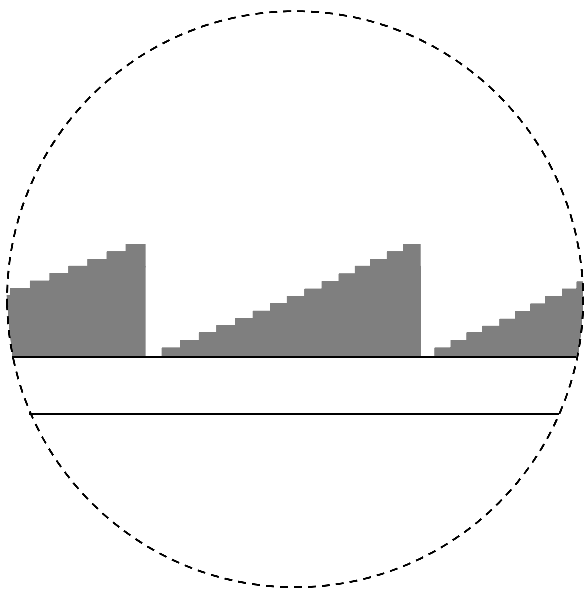

Figure 7. Single-sided EUV lens with 15 layers.

Lens Manufacture

A stepped-profile lens can be manufactured by a multilayer e-beam patterning process involving resist masking only on substantially planar surfaces or very shallow surface topographies, as illustrated in Fig. 8. A silicon substrate is initially coated with a thin (e.g. 2-nm) ruthenium layer, a relatively thick (e.g. 40-nm) molybdenum layer, and a second thin ruthenium layer. The Mo deposition can include several very thin (e.g. 0.2-nm) Si depositions, not shown, to suppress Mo crystallization [2, 4]. The top Ru layer is then patterned, via a standard e-beam lithography with a thin resist mask, to uncover a set of concentric, annular lens zones on the Mo layer. A second Mo layer and a third Ru layer are then deposited, and the Ru is patterned to uncover a second set of annular lens zones wider than the first set. The process is repeated to build up a thick Mo deposition with embedded, patterned Ru layers. The entire structure is then blanket-etched to form the lens, with the Ru layers functioning as etch stops.

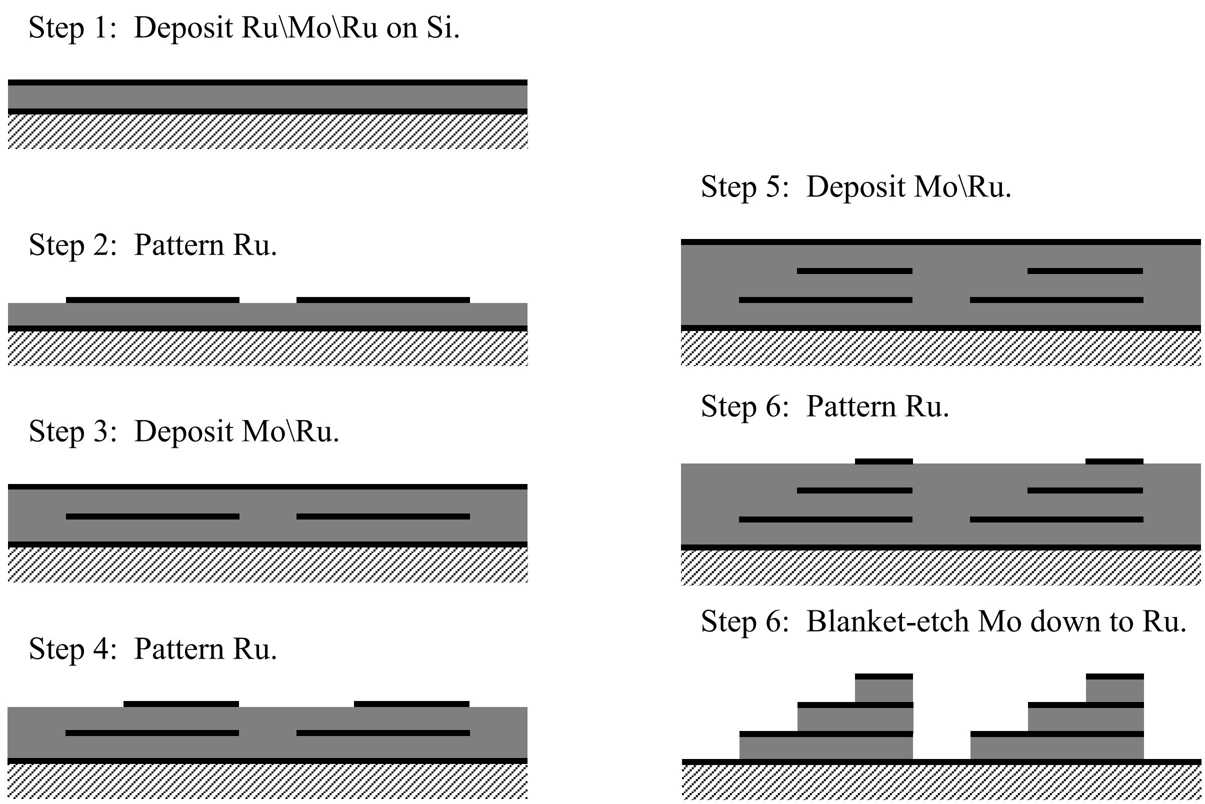

Figure 8. e-beam patterning steps for lens manufacture

Assuming that a positive resist is used for e-beam patterning, the Ru pattern edge at each level will be traversed by the e-beam path during patterning of upper levels. Thus, each Ru pattern can provide an e-beam alignment reference for processing higher-level patterns. (The e-beam will follow a circular or spiral path to image the alignment edge and expose the annular zones.) The combination of thin resist on low surface topography, and self-alignment between process layers, would enable nanometer-scale control over the lens geometry.

For the double-sided lens in Fig. 6, the small-scale (quarter-period) lens structure can be formed first; then the lens is inverted and the large-scale structure is formed with the underside structure serving as an alignment reference.

The above-described process provides accurate control over alignment between layers, but it does not provide an alignment reference for the first layer. A primary alignment reference pattern can be formed as an array of small, circular gold pads, which are placed at the lens center locations using a combination of optical interference lithography and e-beam lithography. The pads can be placed on either the frontside or the backside of the silicon substrate. Fig. 9 illustrates concave and convex lens forms with a frontside alignment pad. The lenses are designed to have a thickness minimum at the lens center, so all of the ruthenium patterning steps will need to expose the resist over the gold pads and alignment imaging will not interfere with patterning.

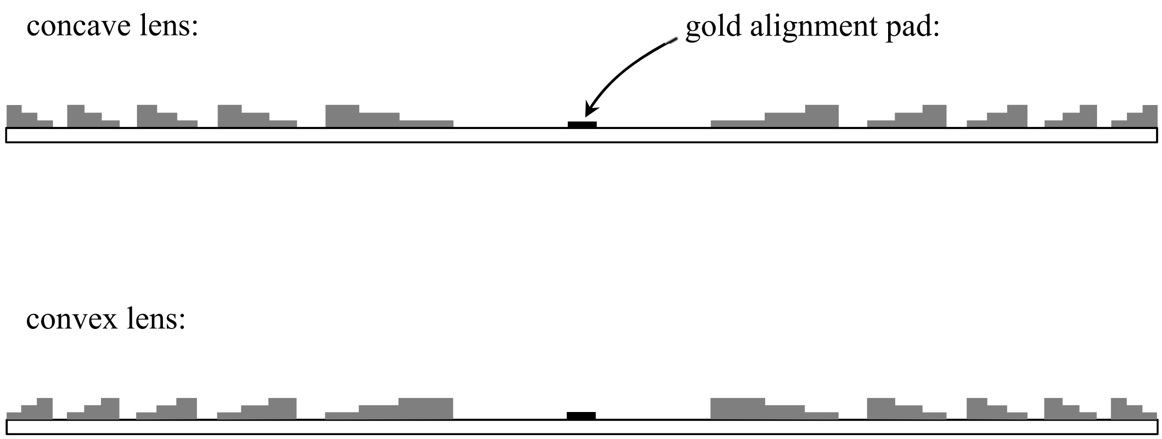

Figure 9. concave and convex lens forms with frontside alignment targets

The gold targets would have better e-beam image contrast than ruthenium and could be used for aligning all the ruthenium layers, not just the first layer. The gold targets could be removed after lens processing, but they are probably too small to significantly affect lens performance even if they are not removed.

An array of circular alignment pads can be formed on a triangular centering pattern via three-beam optical interference lithography [5, 6]. Isolated intensity maxima will be formed on the triangular grid if the three beams are polarized in their planes of incidence, whereas intensity minima will be formed if the beams are polarized parallel to the lens substrate. The interference pattern's period would typically be two orders of magnitude smaller than the lens array period, so a subset of the alignment spots would define the lens centers. After initially forming the gold pads via optical interference lithography, subsequent e-beam lithography processing would be used to accurately locate the pad centers, trim the lens center pads to a small diameter, and remove all other pads.

References

[1] P. P. Naulleau et al., “Electro-optical system for scanning microscopy of extreme ultraviolet masks with a high harmonic generation source”, Opt. Express 22, 20144-20154 (2014) https://doi.org/10.1364/OE.22.020144

[2] K. Johnson, “Application of EUV Diffraction Optics for Actinic Mask Inspection and Metrology”, 2018 EUVL Workshop
https://euvlitho.com/

[3] I. Mohacsi et al., “Fabrication and characterization of high-efficiency double-sided blazed X-ray optics,” Opt. Lett. 41(2), 281–284 (2016)
https://www.psi.ch/lmn/XrayoptEN/Highlight_January_2016.pdf

[4] F. H. Salmassi et al., “Fabrication and performance of transmission engineered molybdenum-rich phase structures in the EUV regime (Conference Presentation)”, Proc. SPIE 10450, International Conference on Extreme Ultraviolet Lithography 2017, 104501B (16 October 2017) https://doi.org/10.1117/12.2281487

[5] J. de Boor, N. Geyer, U. Gösele, V. Schmidt, “Three-beam interference lithography: upgrading a Lloyd’s interferometer for single-exposure hexagonal patterning”, Opt. Lett. 2009, 34, 1783.
http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.658.1651&rep=rep1&type=pdf

[6] M. C. Hutley, “Optical techniques for the generation of microlens arrays”, Journal of Modern Optics, Vol. 37(2) (1990), pp. 253-265.
https://doi.org/10.1080/09500349014550321