EUV Transmission Lens Design and Manufacturing Method

Kenneth C. Johnson kjinnovation@earthlink.net 7/16/2018
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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.

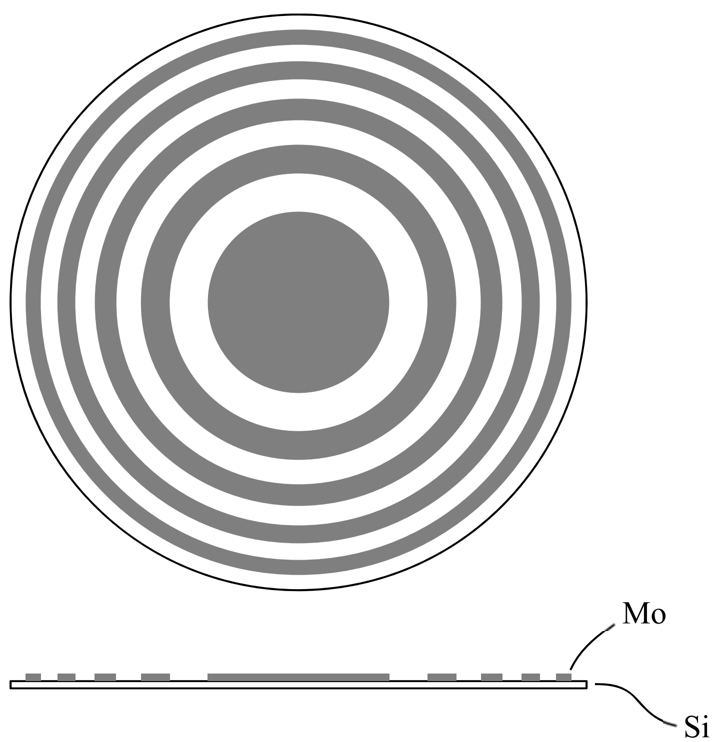


Figure 1. Plan view and cross-section of a zone-plate lens, which has a rectangular zone profile.

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.

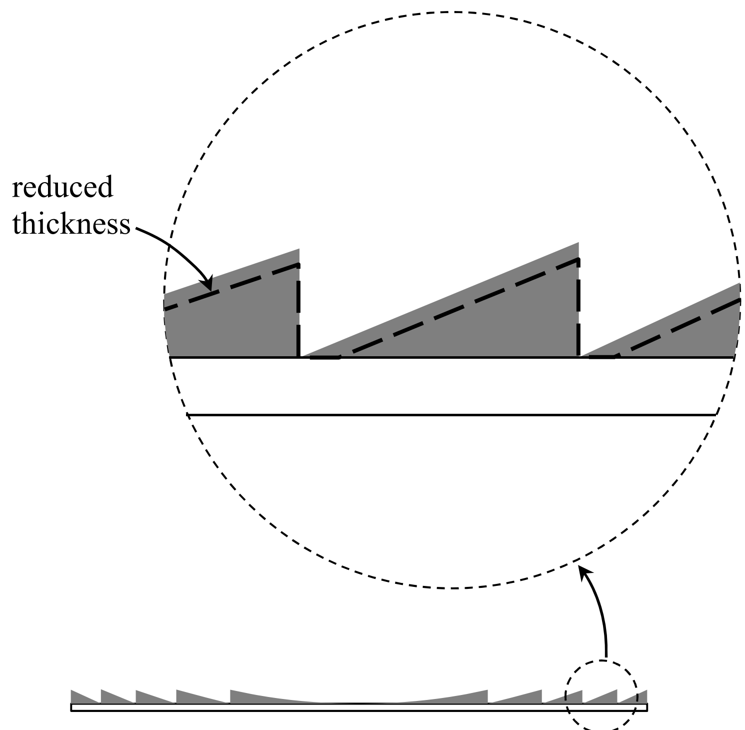


Figure 2. Cross-section of a sawtooth-profile phase-Fresnel lens (standard and thickness-reduced).

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 $1+4m$ for integers m (Fig. 4). The high-order scattering can be reduced by using more layers, at the cost of more process complexity.

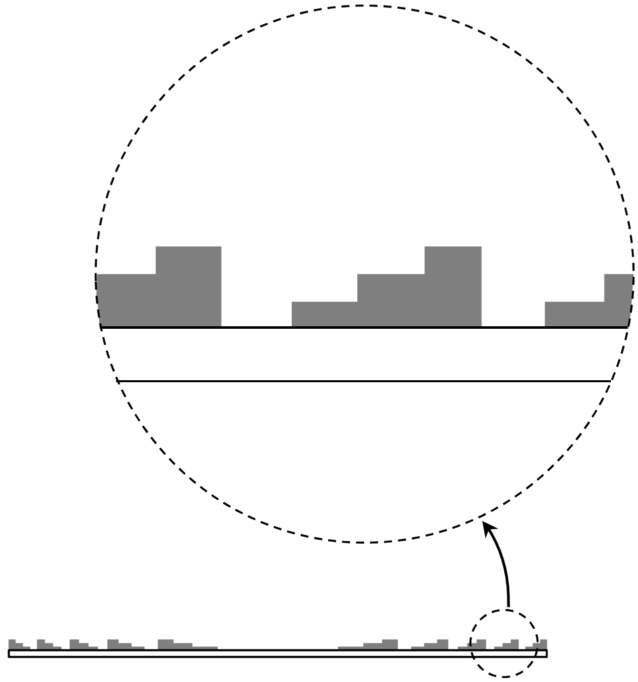


Figure 3. Cross-section of a stepped, 4-level phase-Fresnel lens.

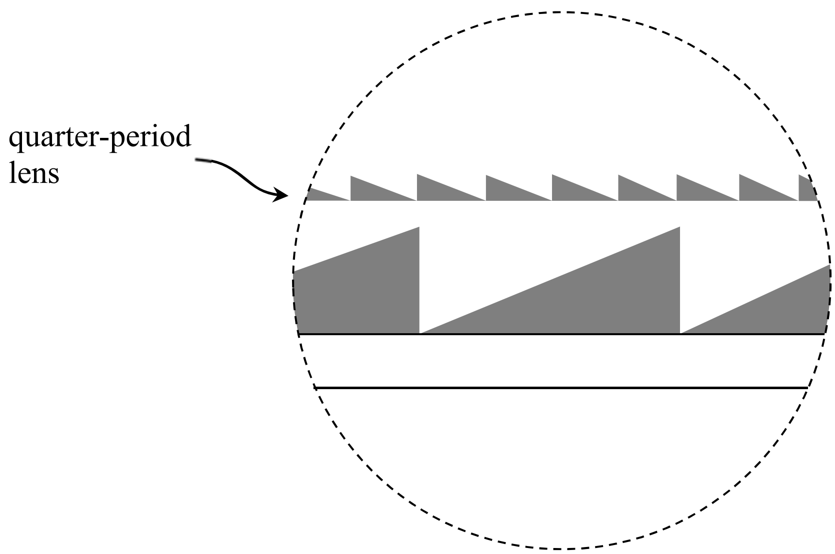


Figure 4. Two stacked phase-Fresnel lenses, equivalent to the stepped-profile lens of Fig. 3.

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.

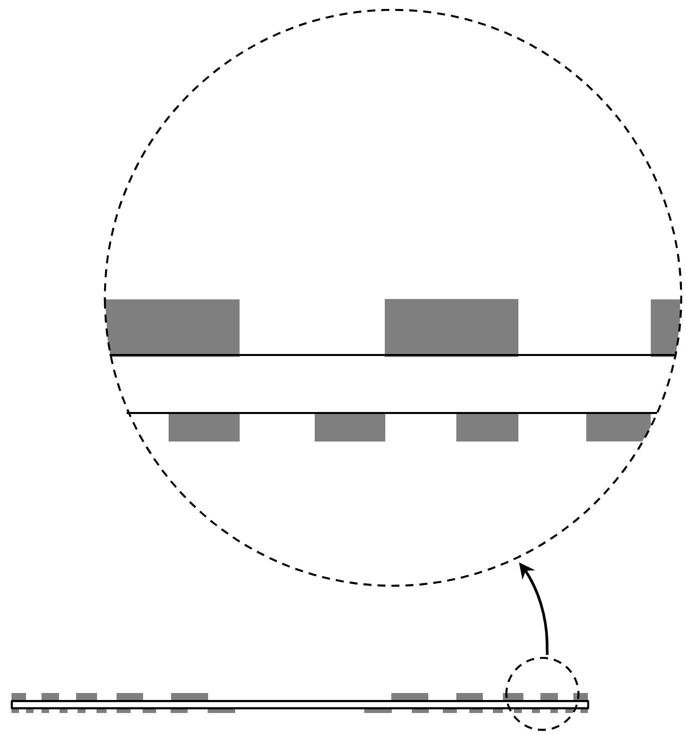


Figure 5. Double-sided EUV lens with zone-plate structures on both sides.

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).

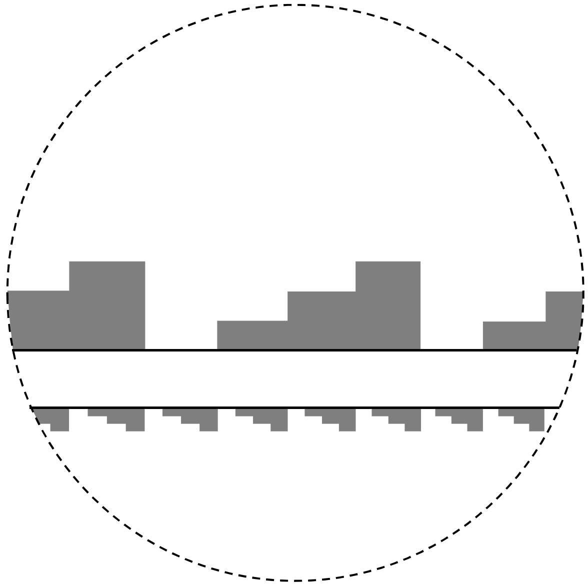


Figure 6. Double-sided EUV lens with 3 layers on each side.

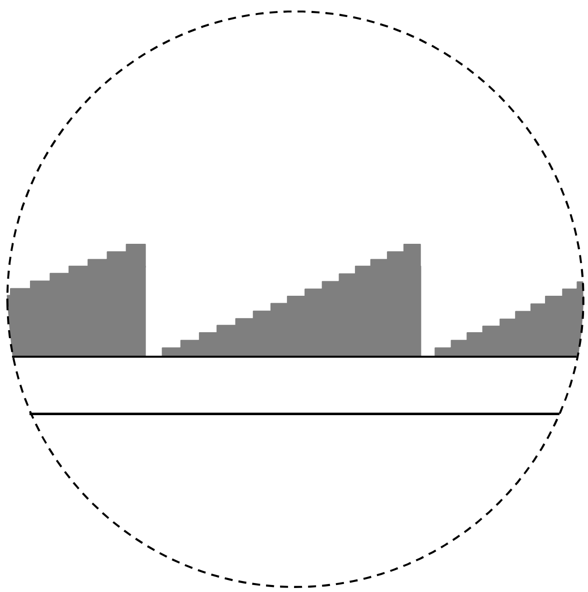


Figure 7. Single-sided EUV lens with 15 layers.

<u>Lens Manufacture</u>

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.

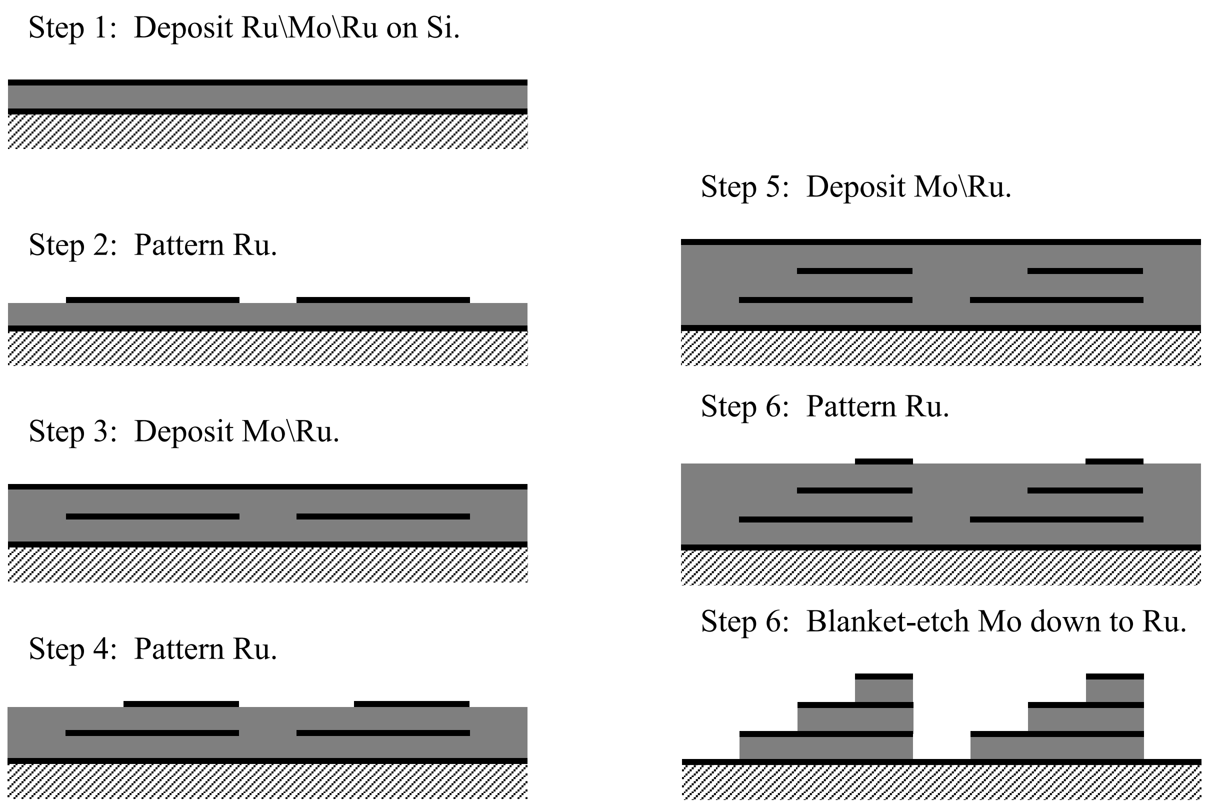
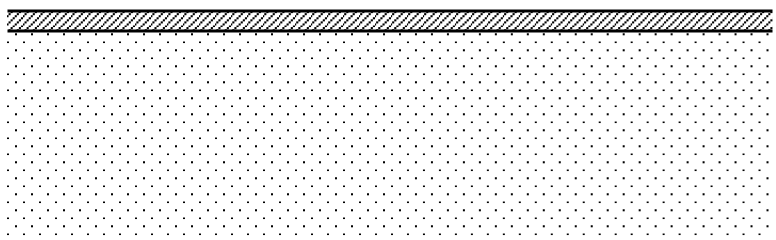


Figure 8. e-beam patterning steps for lens manufacture

An actinic inspection system could require a very large microlens array, e.g. two million lenses distributed over a 20-mm-by-150-mm aperture [2]. The e-beam write time might be many days per process layer. Nanometer-scale placement and alignment accuracy can be achieved over such large areas and time scales by using alignment holes or posts formed between the lenses. (Alternatively, the central zone of each lens could be formed as a circular hole, which would serve as an alignment mark.) An alignment hole fabrication process for a double-sided lens is illustrated in Fig. 9.

A sacrificial substrate (e.g. nitride) is initially coated with a thin (e.g. 2-nm) Ru etch-stop layer, a thicker (e.g. 20-nm) Si lens substrate layer, and a second thin Ru etch-stop layer. A periodic array of alignment holes is then formed in the structure via optical interference lithography. For example, an array of circular alignment holes can be formed on a triangular centering pattern via three-beam optical interference lithography [5, 6]. Isolated intensity maxima can 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 much smaller than the lens array period, so a subset of the interference extrema would lithographically isolated to define the alignment spots, and e-beam lithography could be used to locate the alignment hole centers and open up the holes to a square shape. A Mo layer with embedded, patterned Ru etch-stop layers is then built up by the process illustrated in Fig. 8, Steps 1-5. A second sacrificial substrate is deposited, the structure is inverted, and the first sacrificial layer is removed. The first Ru layer serves as an etch mask for re-forming the alignment holes in the second substrate. A second Mo layer with embedded, patterned Ru etch-stop layers is formed, and then both sides of the structure are etched down to the Ru to remove the sacrificial substrate and form the lens profile.

Step 1: Deposit Ru\Si\Ru on sacrificial substrate.



Step 2: Form alignment holes via optical interference lithography.

Step 3: Deposit Mo with embedded, patterned Ru etch-stop layers.

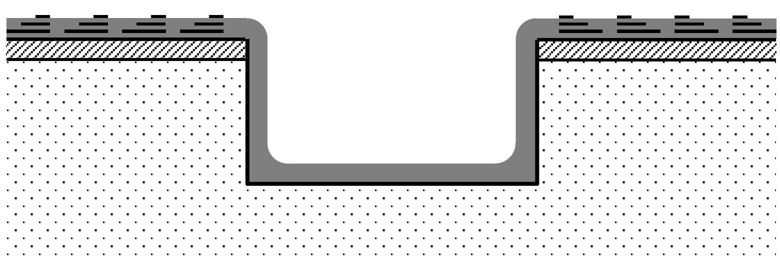


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Figure 9. e-beam alignment hole

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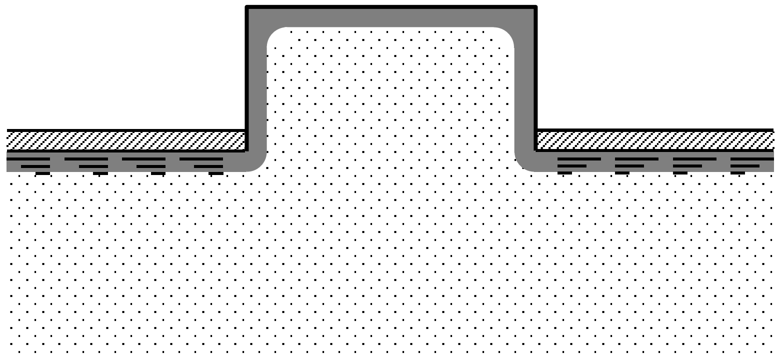
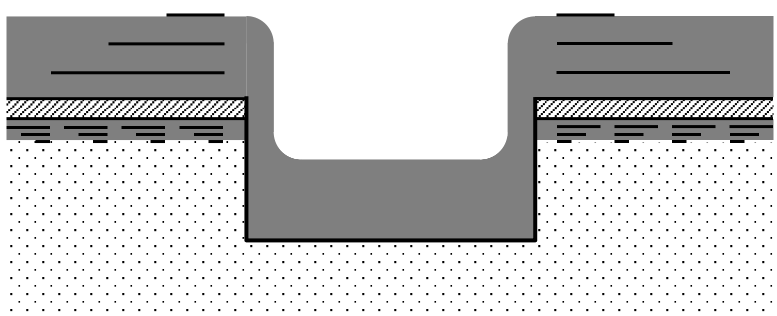
Step 4: Deposit second sacrificial substrate, invert the structure, remove the first sacrificial substrate.



Step 5: Etch out the alignment holes.

Step 6: Deposit Mo with embedded, patterned Ru etch-stop layers.



Step 7: Etch both sides down to the Ru layers.

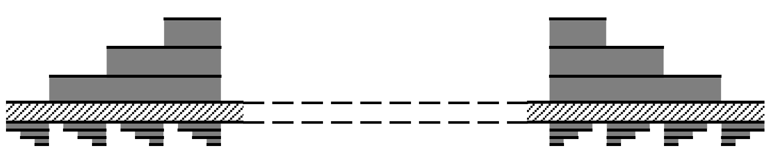


Figure 9. e-beam alignment hole

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