Aperiodic Multilayer Mask Optimization for High-NA and Hyper-NA Extreme Ultraviolet Lithography – Reflectance, Polarization, and Phase

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As extreme ultraviolet lithography tools with higher image numerical apertures (NA_i) are introduced, the range of angles at the multilayer (ML) mask stack is also increased. For a 4X reduction EUVL system, the mask numerical aperture (NA_m) increases from 0.0825 at 0.33NA_i to 0.1375 at 0.55NA_i (high-NA), and to 0.1875 at 0.75NA_i (hyper-NA). This represents a challenge for maintaining through-angle mask reflection using the current periodic mask multilayer structures. As reflectance is reduced at larger mask angles, an amplitude apodization effect will result, which is asymmetrical about the systems CRAO. Additionally, phase error effects increase, which can lead to both symmetrical and asymmetrical image degradation. Both amplitude and phase variation are further complicated by polarization effects that increase at these larger angles. Splitting a ML stack into separately designed periodic regions to broaden angular performance has been reported [1]. In this paper, we present approaches to the optimization of *aperiodic* multilayers for through-angle reflectance, phase, and polarization effects for high-NA and hyper-NA applications.

Conventional EUVL photomasks are designed around the same principles as EUVL reflective optics, using molybdenum and silicon periodic ML stacks of the general form (MoSi)^40. The grading of lens MLs, both laterally and through depth, has been used to accommodate the range of angles incident at lens elements [2]. Previous optical coating multilayer optimization studies have shown that relatively flat reflectivity profiles can be created with aperiodic multilayers for lens NA values up to 0.3 [3]. EUVL photomasks must support a broad range of patterns and illumination types and have thus far been less suited for grading. With the use of periodic multilayers, falloff of reflectance amplitude through angle is a result. In addition to reflectance amplitude, the phase of reflected light, which plays an important role in imaging, is also strongly influenced by increasing angles [4]. The propagation of light through each bilayer in the stack imparts a phase shift based on incidence angle. This is then accumulated over many layers, inducing phase effects which are unique to each illumination point. This will become especially true for high-NA and hyper-NA mask applications.

The optimization approach we present is a process using adaptive heuristic search (i.e. genetic) algorithms. While designing a particular periodic EUV ML system fundamentally involves two controllable variables (the ML period and Mo:Si ratio), aperiodic multilayers have as many optimizable variables as there are layers. Using a two-step design approach, we use a genetic algorithm to produce unique ML solutions for each layer pairing. This is then followed by a gradient descent optimization to locate local maxima. As a result, we have designed large angle mask multilayers which have improved reflectivity, enhanced TE polarized reflectance, and reduced phase error effects. When used for lithographic imaging at 0.55 NA and above, optimized aperiodic multilayers show improved NILS and strongly enhanced peak aerial image intensity. We show that inclusion of phase and polarization optimization in aperiodic ML designs can extend 0.55 NA_i imaging to 14nm pitch, and 0.80 NA_i to 12nm pitch (as shown in Figures 1 and 2), which beyond what would be possible with conventional periodic layers.

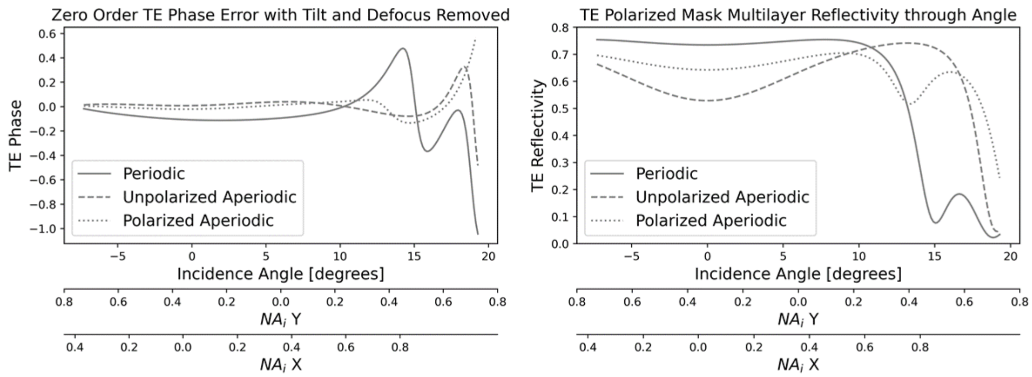

Fig. 1. Multilayer phase and amplitude of optimized MLs through angle (computed using RCWA). Compared are three multilayers - a periodic multilayer similar to current mask MLs, an aperiodic multilayer optimized for unpolarized reflection over the range of angles used at 0.8 NA_i, and an aperiodic multilayer designed to enhance TE polarized reflection. The left plot shows zero order (undiffracted) phase error, with tilt and defocus removed. The aperiodic layers maintain low phase error over a wider range of angles compared to the periodic multilayer structure. The right plot shows TE reflectivity, with strong asymmetrical apodization of which some is recovered by the aperiodic designs.

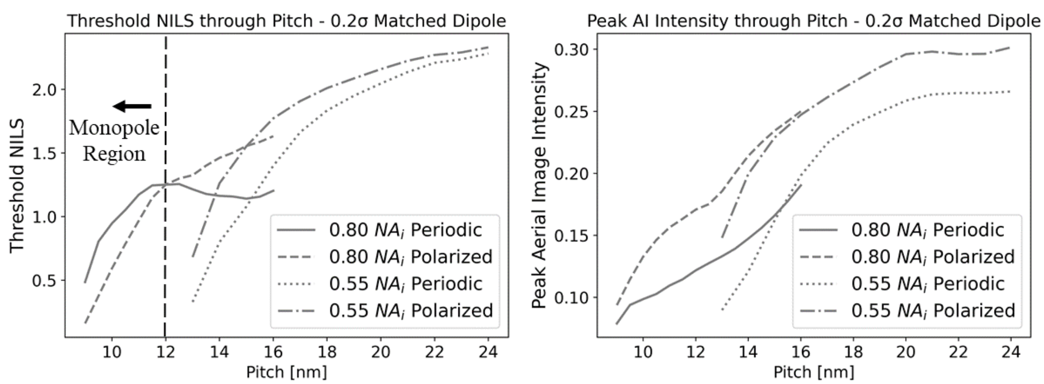

Fig. 2. Threshold NILS and peak aerial image intensity (AI) plots computed using RCWA for 0.55 NA_i and 0.80 NA_i using 0.2σ matched dipoles for 1:1 features. For 0.55NA_i, NILS for the polarized aperiodic ML at 14nm is near 1.5 with a strong gain in peak AI over the periodic ML. For 0.8NA_i, NILS for the polarized aperiodic at 12nm is near 1.25 and near 1.5 near 13nm, with a large gain in AI compared to the periodic ML.

[1] A. Erdmann *et al.*, in *Extreme Ultraviolet (EUV) Lithography IV* (SPIE, 2013), pp. 495–506.
[2] P. Lee, Appl. Opt., AO **22**, 1241 (1983).
[3] A. E. Yakshin *et al.*, Opt. Express, OE **18**, 6957 (2010).
[4] M. F. Bal, J. Micro/Nanolith. MEMS MOEMS **3**, 537 (2004).