Lamellar ridge gratings for DUV excimer lasers

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Because of its high angular dispersion a grating in Littrow mount is the main component for narrowing the laser line of DUV lithography excimer lasers. Rigorous theoretical investigations show that lamellar ridge gratings can reach up to more than 90% efficiency. This result can also be explained by thin film optical theory. Additionally, we present first results of patterning ridge gratings.

1 Introduction

Excimer lasers are used for illumination and imaging in DUV-photolithography (λ = 248nm, 193nm). In order to keep chromatic aberrations sufficiently small, the laser line has to be narrower than 2pm. The main component of the line narrowing module is a high dispersive grating in Littrow mount. The corresponding dispersion relation $d\theta_d / d\lambda = 2 \tan \theta_d / \lambda$ tells one to use a large diffraction angle θ_d for high dispersion. The generally used angle $\theta_d = 80°$ is also used here. With echelle gratings operated in diffraction orders higher than 80, diffraction efficiencies of 70%–80% are reached. Respective investigations for coated echelles can e.g. be found in [1]. In this report the results of efficiency calculations of a special type of lamellar gratings are presented. The significant difference to echelles is that they can be used in orders 1 to 5 and higher. Additionally a simple explanation is given using thin film optical theory for the high diffraction efficiency. Furthermore measurements of a first fabrication test of such gratings are presented.

2 Maximum obtainable efficiency

Littrow mount in 1st and 2nd order for DUV wavelengths of 248nm and 193nm lead to grating periods which are too small for standard patterning techniques. So, we consider 3rd order Littrow mount which is characterized by the condition $\sin \theta = 3\lambda/(2d)$. From $\sin(\theta_d = 80°) = 0.98$ it follows $d/\lambda \cong 3/2$ leading to a grating period of about 300nm for λ =193nm which is feasible by today's technology.

Rigorous theoretical investigations using the exact and flexible finite element method DIPOG [2] show that high efficiency for the given large diffraction angle can only be reached if extremely narrow ridges between w = 10nm and w = 35nm can be realized (cf. Fig. 1 for efficiency and Fig. 2 for a scheme of the ridge gratings). We investigated aluminium as well as dielectric silica ridges for various widths and heights, vertical or inclined by an angle in several diffraction orders corresponding to different grating periods. All these types reach high efficiency if the ridges are sufficiently thin. Maximum efficiency is reached by an

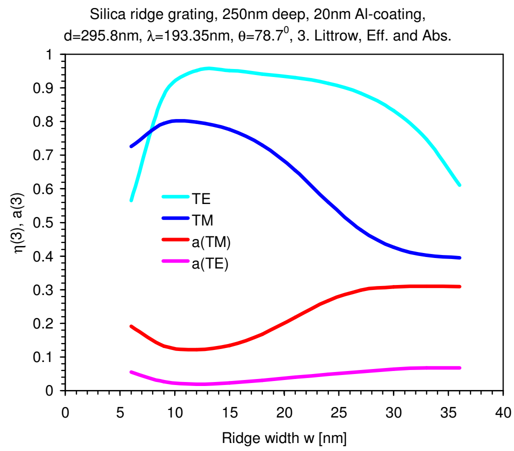

Fig. 1 *Efficiency and absorption of a 250nm deep silica ridge grating with period d = 295.8nm in 3rd order Littrow mount for TE- and TM-polarization over the ridge width.*

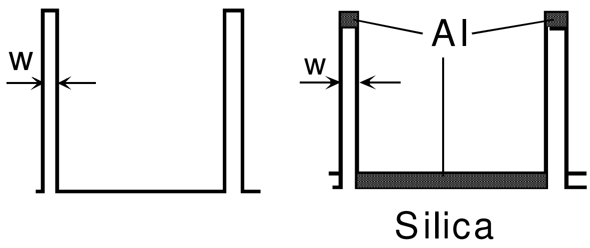

Fig. 2 *Lamellar ridge gratings consisting of a single material like Al or silica (left) or silica coated with a thin Al layer of 10 to 20nm.*

additional thin Al layer of 10 to 20nm (cf. Fig. 1) on the silica ridges as outlined in the right part of Fig. 2. Trapezoidal ridges reduce the efficiency drastically: already 80° slope (instead of 90°) make the efficiency drop below 50% assuming ridges with 10nm top width. Optimal height of the ridges for maximum efficiency is between 250nm and 350nm depending on diffraction order and polarization. Optimal height for 1st order Littrow mount is between 50 and 80nm.

3 Fabrication of ridge gratings

Ridge profile gratings can be patterned by holographic recording in photoresist and subsequent ion etching into the substrate surface using the photoresist grooves as masks. Fig. 3 shows photoresist groove profiles with a period of 420nm, a depth of 215nm and ridge width of 120nm measured by AFM. The transfer into the substrate by Ar^{+} ion beam etching results in 100nm deep ridges with 50nm FWHM as measured in Fig. 4.

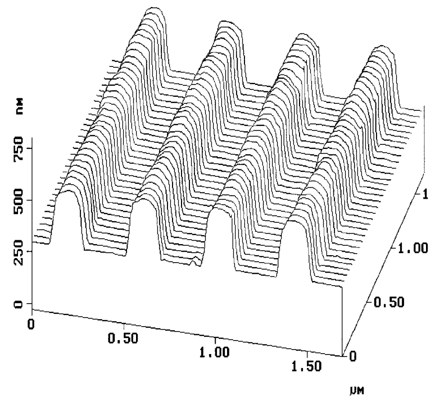

Fig. 3 *Measured resist profile of a lamellar ridge grating.*

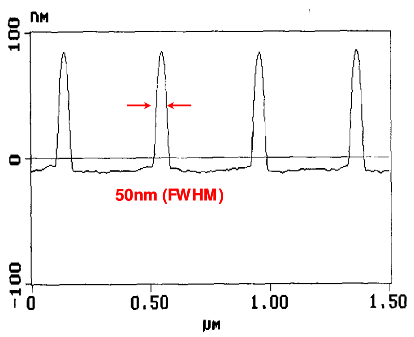

Fig. 4 *AFM measured substrate profile (ULE) after transferring the above resist mask profile by ion beam etching. First patterning test of a lamellar ridge grating.*

Obviously, the first fabrication test needs to be improved: the ridges have to become deeper, narrower and the sides steeper. A more successful technique might be e-beam writing with subsequent reactive ion etching.

4 Explanation of the high diffraction efficiency

The diffraction of a dielectric lamellar ridge grating can be described by the principle shown in Fig. 5a: Due to the large Littrow angle of 80° and the height-to-period ratio of about 1 an incoming plane wave strikes only 4 to 5 ridges. At each ridge reflection (and transmission) occurs. The reflected parts constructively interfere since the Littrow condition is fulfilled for the 3^{rd} diffraction order.

A stack of a dielectric multilayer with N=4 or N=5 double layers of silica and air with period p comparable to the grating period (cf. Fig. 5b) works analogously, also yielding high reflectance (Fig. 6)

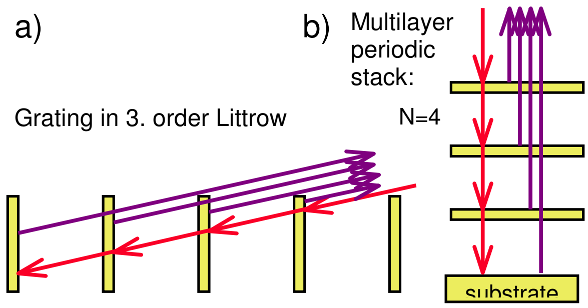

Fig. 5 *a) Ridge grating b) dielectric multilayer stack. Red arrows: Incoming ray as a representation of a plane wave and its reflections at each of the ridges (left) or layers (right). Violet: diffracted rays which constructively interfere if they are in phase.*

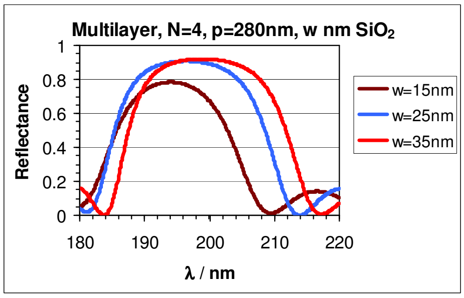

Fig. 6 *Reflectance of a multilayer stack of four double layers of period p = 280nm with each double layer consisting of a silica layer of thickness w and the rest of air.*

as calculated with thin film optical theory. Small differences to the grating model result from e.g. additional reflections at the bottom of the grating grooves not considered in the thin film model.

5 Summary

Lamellar high dispersive gratings in a low Littrow order mount with thin ridges of 15 to 35nm yield high diffraction efficiency of up to 95% if the depth is about the period. The underlying physical mechanism can also be explained by thin film optical theory. First measurement of ridge gratings fabricated by holographic recording and subsequent ion beam etching is presented. A further improvement might be achieved by e-beam writing of a template and Nano-Imprint replication.

References

[1] B. H. Kleemann, J. Erxmeyer, „Independent electromagnetic optimization of the two coating thicknesses of a dielectric layer on the facets of an echelle grating in Littrow mount“ in *J. mod. Opt.* **51**: 2093-2110 (2004)

[2] J. Elschner, G. Schmidt, „Numerical solution of optimal design problems for binary gratings” in *Journ. Comp. Physics* **146**: 603-626 (1998)