Fabrication of Polarizer by Metal Evaporation of Fused Silica Surface Relief Gratings

Bálint KISS[*1,2], Roland FLENDER[*2], Judit KOPNICZKY[*2], Ferenc UJHELYI[*3] and Csaba VASS[*1,2]

[*1] ELI-Hu Nkft., Dugonics ter 13, H-6720 Szeged, Hungary
E-mail: Balint.Kiss@eli-alps.hu
[*2] Department of Optics and Quantum Electronics, University of Szeged, H-6720 Szeged, Dóm tér 9, Hungary
[*3] Department of Atomic Physics, Physical Institute, Budapest University of Technology and Economics, Hungary

Our aim was to produce metal-wire grating polarizers by a simple two-step method. First, fused silica surface relief gratings were generated by two-beam interferometric laser-induced backside wet etching (TWIN-LIBWE) technique. The grating period was varied from 150 nm to 860 nm (p=150, 280, 460, 860 nm) by the changing of the incident angle of interfering beams. In the second step the gratings were selectively evaporated by thin silver (Ag) film using near grazing incidence (80^{o}) arrangement to produce narrow metal wires. The thickness of metal film was 30±5 nm. The morphology of fabricated metal-wire structures were studied by scanning electron microscopy. The polarizers were tested in infrared wavelength range (λ=1532 nm). According to our measurements, the polarisation contrast of 280 nm period structures was 1:10 for TE:TM transmitted modes. In this case the filling factor of metallic stripes are close to 0.7.

DOI: 10.2961/jlmn.2015.01.0011
Keywords: polarizer, periodic structure, metal wire grating

1. Introduction

Metal-wire gratings are metallic periodic structures which provide polarization state dependent transmission/reflection of light and consequently can be used as polarizing beam splitters in optics and optical telecommunications [1,2]. If the spatial periodicity of the metal lines are much smaller than the wavelength of incident light, the metal structure reflects the light polarized parallel to the grooves (TE mode) and transmits the light polarized perpendicular to the lines (TM mode) with high efficiency [3,4]. As the period is comparable to the wavelength of light, the theoretical description becomes sophisticated using vectorial solutions of Maxwell equations based on rigorous coupled wave analysis (RCWA), or other numerical methods [5-7]. Concerning the mid- and far infrared region, the suitable polarizers are the free standing metal wires [8] and periodically structured metal films [9,10].

In the latter case, the parameters of the periodic metallic structure (profile geometry, metal thickness, etc.) can be optimized to achieve even spectrally broadband polarization properties in the IR [11] and visible [12]. The production of such fine structures are usually based on multistep lithographic techniques [12-14], which realize periodically patterned metallic coating on a flat substrate.

Recently it has been shown that transmission gratings produced by two-beam interferometric laser induced backside wet etching technique [15] (TWIN-LIBWE) are suitable as light coupler elements [16] or as master gratings in imprint lithography [17].

In this experimental work, we present a relatively simple two-step method to realize narrow metallic lines on a periodic surface, which are acting as light polarizer. It based on the fabrication of surface relief gratings into fused silica substrate and the subsequent selective coating of the grooves by metallic film.

2. Experimental

As the first step, surface relief gratings were etched into the 1 mm thick fused silica plates by two-beam interferometric laser-induced backside wet etching (TWIN-LIBWE) technique based on a Q-switched frequency-quadrupled Nd:YAG laser source (λ=266 nm, τ_{FWHM}=8 ns, repetition rate: 10 Hz). The experimental setup was detailed in our previous study [15] and the scheme is plotted in Fig. 1.

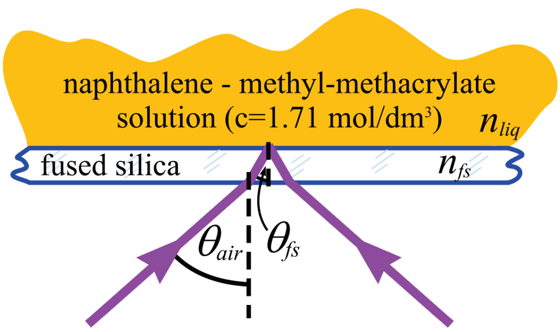

Fig. 1 Scheme of the experimental setup for grating fabrication into fused silica substrate

The period (p) of the interference pattern, and therefore the period of the etched gratings can be calculated by (1) equation, where λ_{air}, λ_{fs} and θ_{air},θ_{fs} are the wavelength and incident angle of the beam in the air and fused silica, respectively.

$$p = \frac{\lambda_{fs}}{2\sin(\theta_{fs})} = \frac{\lambda_{air}}{2\sin(\theta_{air})} \quad (1)$$

The number of laser pulses was changed between 1 and 150; the laser fluence was varied within the range of 270 and 330 mJ/cm^2. The liquid absorber was saturated solution of naphthalene and methyl-methacrylate (c=1.71 mol/dm^3). The grating period, "p" (150, 280, 460 and 860, nm) were adjusted by the incident angles (θ=62.5°, 28.4°, 16.8° and 8.9°) of the spatially and temporally overlapping laser beams.

In the second step the grooved surfaces were selectively evaporated by thin silver (Ag) films using near grazing incidence (Fig. 2.). The angle of incidence was set to 80°, while the grooves were perpendicular to the plane of incidence.

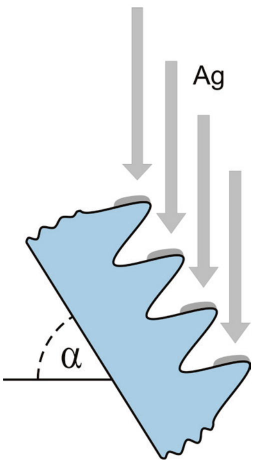

Fig. 2 Scheme of Ag film evaporation onto the grooved surface at near grazing incidence: α=80°, target-gun distance is 30 cm.

This arrangement helps to create narrow conducting lines on the surface of the dielectric structure by shielding some part of every individual groove by the next one. This self-masking effect is primary controlled by the angle α in Fig. 2. Similar evaporation method was applied earlier in references [4,12] for example.

The surface characterization of transmission gratings was carried out by atomic force microscopy (AFM) using contact mode, while the evaporated silver structures were observed by scanning electron microscopy (SEM). The thickness of the evaporated films was measured by profilometer.

The polarization contrast and the transmission of the produced structures were tested by a diode laser (λ=1532 nm) with polarization maintaining fiber. In order to rotate the plane of polarization, a half wave plate was inserted into the beam before the sample, and the signal transmitted through the sample was detected by a photodiode (Fig. 3.).

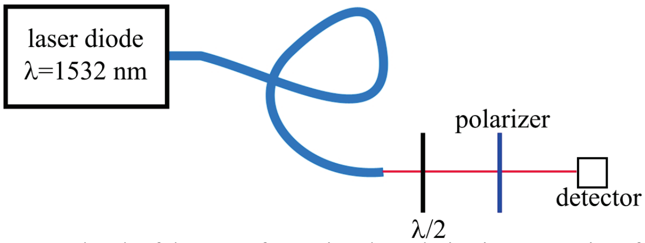

Fig. 3 Sketch of the setup for testing the polarization properties of the produced periodic silver surfaces.

3. Results

3.1 Surface characterization

Reference surfaces coated by Ag film at grazing incidence (α=80°) were generated automatically at the non-grooved areas of fused silica plates (Fig. 4.). The distribution of the silver is homogeneous and the thickness is measured to be 30±5 nm in all cases. Since the distance between the Ag source and the target was around 30 cm, it is feasible to assume that the film thickness measured at the non-grooved area is equal to the thickness of Ag deposited on the surface of grooves.

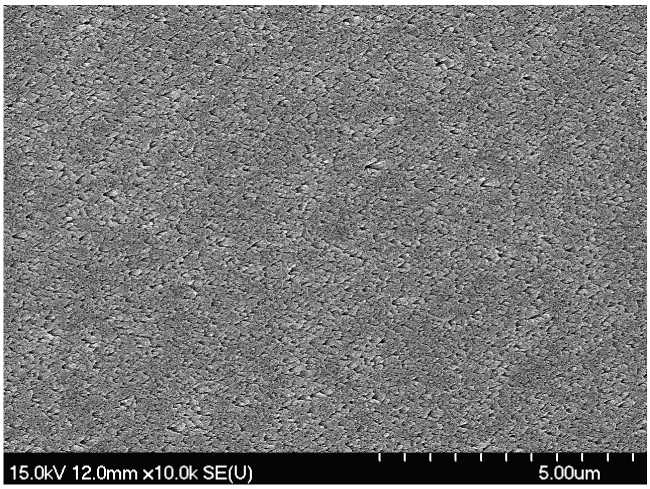

Fig. 4 SEM image of reference surface coated by Ag film at grazing incidence

It is important to understand the formation of silver patterns on the surface of grooves having different modulation depth (MD), and consequently different level of self-masking effect occurring, during fixed evaporation conditions. In order to find the optimal MD for each periodicity, several series of grooved spots were created having different MD, by adjusting the laser fluence and the pulse quantity.

An example sequence of the AFM topographies of gratings having 860 nm period with different MD are plotted in Fig. 5, and the corresponding SEM images after selective Ag coating of them can be seen in Fig. 6.

If the modulation of the master surface is moderated (~ 4 nm in Fig. 5a), the silver forms a quasi-continuous film (Fig. 6a) on fused silica at this grating period.

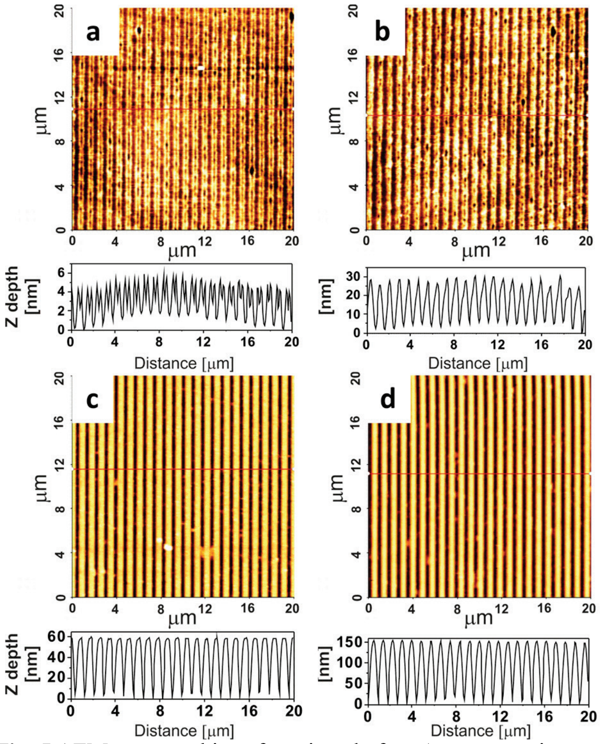

Fig. 5 AFM topographies of gratings before Ag evaporation. Etching parameters: p=860 nm, F=283mJ/cm^2
(a) 4 pulses, MD=4 nm
(b) 6 pulses, MD=20 nm
(c) 8 pulses, MD=60 nm
(d) 30 pulses, MD=150 nm

However the grooved surface with average MD of 20 nm (Fig. 5b) is suitable to create separated metallic lines (Fig. 6b).

With increasing MD of the master structure the metallic wires become more regular and uniform (inserts *c* and *d* in Fig. 5 and Fig. 6). It is important to note that at fixed evaporation conditions (angle, evaporation rate), the filling-factor (the ratio of metal-covered area and the whole area) of Ag structures also significantly depends on the groove depth of fused silica gratings. The filling-factor of silver lines in Fig. 6 (b), (c) and (d) is measured to be 0.76, 0.66 and 0.61, respectively. This property has impact on polarization properties and transmission of the periodic structure [5, 13].

Decreasing the period of master fused silica grating, the reachable maximal modulation depth decreases, due to the main attributes of TWIN-LIBWE procedure [15]. Fig. 7 and 8 summarize the surface characteristics of evaporated grooves by increasing grating period and consequently increasing MD. In case of the smallest period of p=150 nm (Fig 7a), the grooves are entirely covered by the Ag film (Fig. 8a), due to the moderate reachable modulation (8-10 nm) of the surface: the grooves do not shield the neighbor ones effectively enough. The 280 nm grating period (Fig. 7b) makes it possible to create structures have higher average MD (20 nm) which supports the formation of periodic Ag structure consist of individual silver lines (Fig. 8b). The uniformity of Ag lines are increasing with the increasing of groove spacing and modulation depth (Fig. 7c and 8c) and found to be the best at p=860 nm (Fig. 7d and 8d).

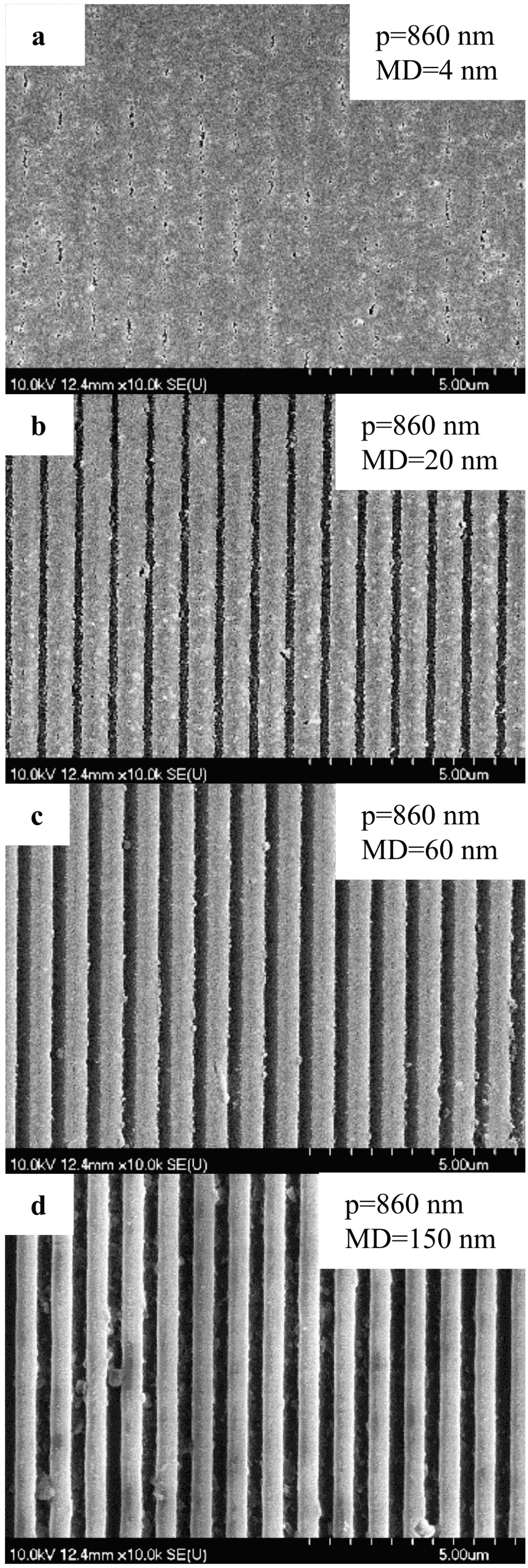

Fig. 6 SEM images of metallic lines created by silver evaporation of gratings on Fig. 5, respectively. The inserts show the period and modulation depth of substrate gratings.

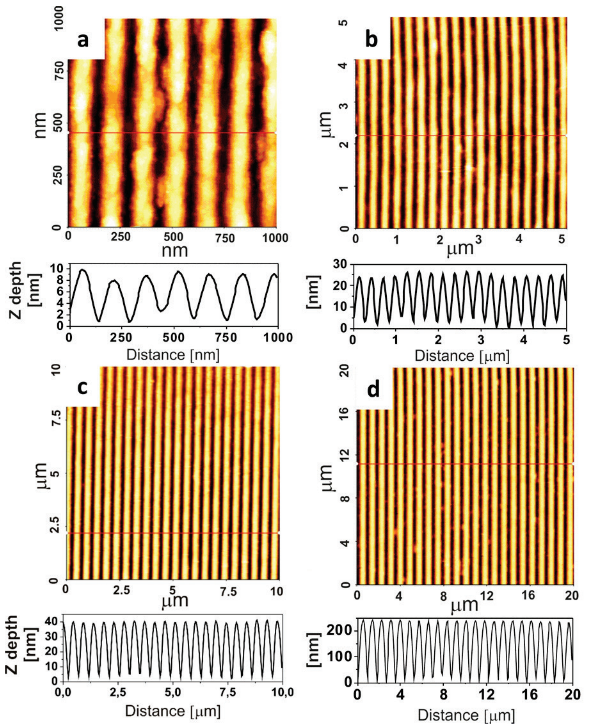

Fig. 7 AFM topographies of gratings before Ag evaporation.
(a) p=150 nm, MD=8-10 nm (F=320 mJ/cm^2, 30 pulses)
(b) p=280 nm, MD=20 nm (F=525 mJ/cm^2, 20 pulses)
(c) p=460 nm, MD=40 nm (F=342 mJ/cm^2, 20 pulses)
(d) p=860 nm, MD=240 nm (F=336 mJ/cm^2, 50 pulses)

3.2 Test measurements

As a demonstration, the polarizing properties of the created Ag structures were tested by a laser source operating at λ=1532 nm (see in Fig. 2). The reference surfaces, as well as the quasi-homogeneously coated surfaces of p=150 nm gratings (Fig. 6a and Fig. 8a) are acting like a metallic mirror with low transmission (≈0,5 %).

The polarization contrast was defined as the ratio of transmitted TM intensities in the case of p and s polarization of illumination, respectively. To compare the polarization contrast of fabricated metallic structures in the function of etching pulse quantity, see in Fig. 9.

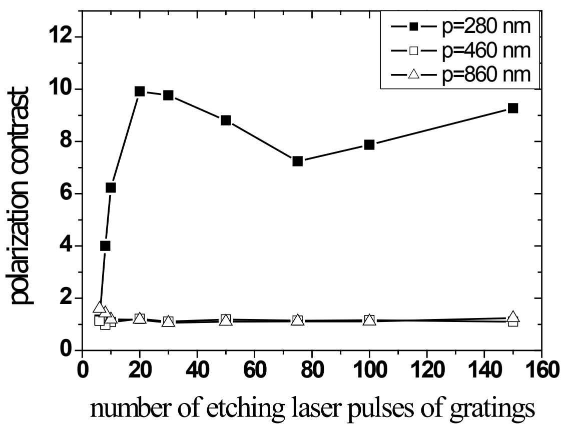

Fig. 9 Measured polarization contrast of the Ag coated gratings.

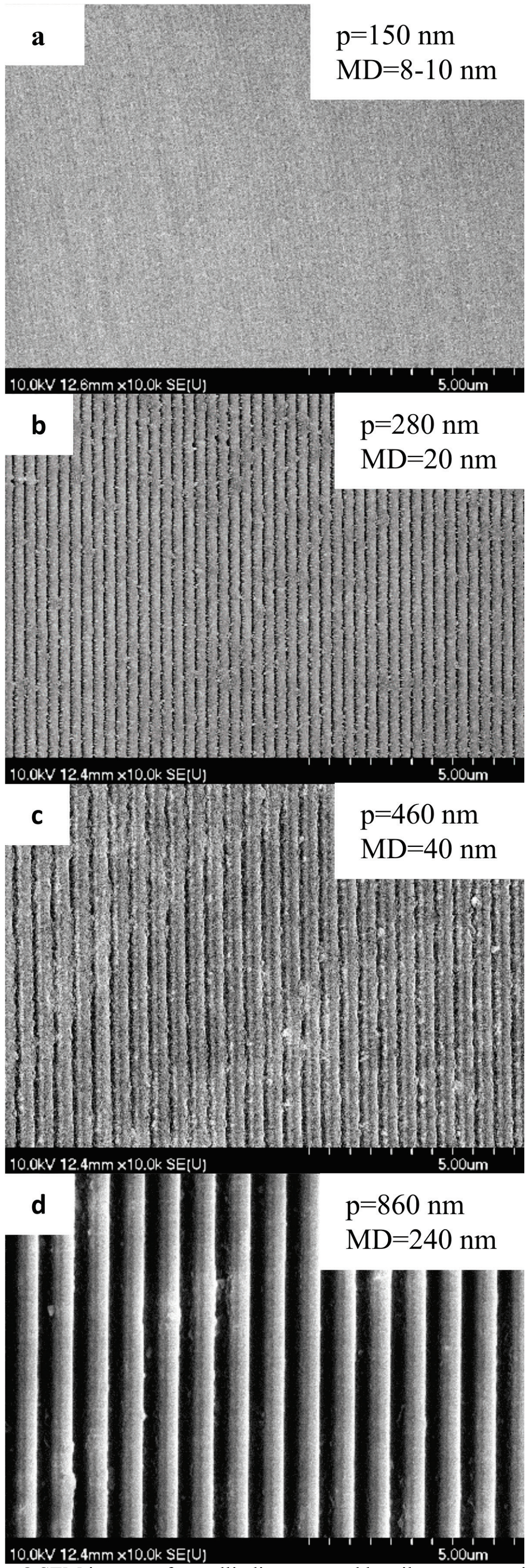

Fig. 8 SEM images of metallic lines created by silver evaporation of gratings on Fig. 7, respectively. The inserts show the period and modulation depth of substrate gratings.

The best efficiency is achieved with the coated p=280 nm period (for example Fig. 8b) gratings. The higher period structures show one order of magnitude lower values at best, however a weak but certain polarizing effect was detectable. This behavior is not surprising, since the effect is disappearing as the groove spacing and the wavelength of illumination are commensurate.

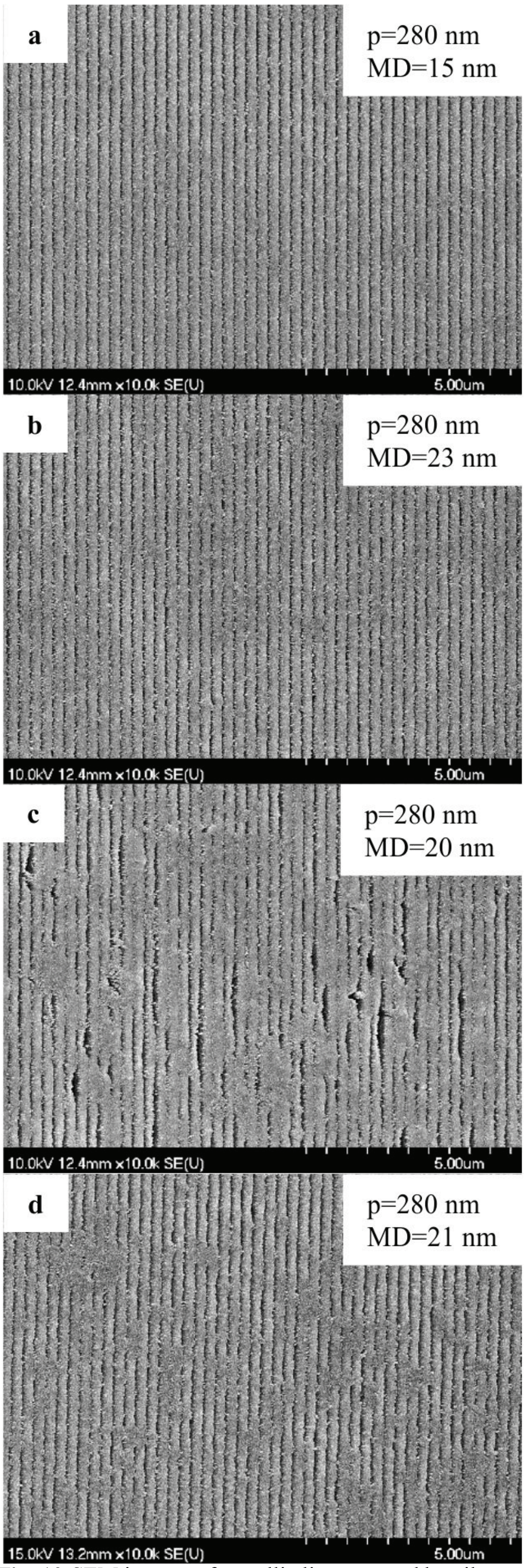

Fig. 10 SEM images of metallic lines created by silver evaporation of p=280 nm gratings. The inserts show the period and modulation depth of substrate gratings.

Considering the most effective grating surfaces with p=280 nm period; the evolution of created metallic surfaces are shown in Fig. 10. The metallic coating is not forming well separated lines if the MD is smaller than ≈10 nm (<6 pulses), consequently the polarization contrast is around unity. The contrast is increasing to around 4 (Fig. 9) with increasing MD (11 nm) and the silver coating forms periodic pattern on the substrate etched by 8 pulses (Fig. 10a).

The maximal polarization contrast is measured to be around 10, here the metal surface consists of separated stripes (Fig. 8b) with filling factor of is 0.77; this surface was the most suitable polarizer structure. A very similar pattern is observable on Fig. 10b, although the Ag lines are not as uniform as in Fig. 8b, but the contrast is still around 10.

Increasing the etching pulses to 75 causing the degradation of master surfaces at this period, and consequently the degradation of the evaporated metallic stripes (Fig. 10c) and the polarization contrast as well. At such low period the wet etching of fused silica becomes less controllable if the number of subsequent laser pulses are too much (>30 in this case) due to the etching properties of LIBWE [15]. In this regime the quality of gratings is varying arbitrary: the grating made by 150 pulses is better again, and also the metallic surface (Fig. 10d), which provides high polarization contrast again.

Besides polarization contrast, the overall transmission is of major importance. Unfortunately, the transmission of the wire gratings were measured to be around 30% at best, which probably related to the thickness and exact shape of metallic lines created on the substrates. The best would be to set the film thickness equal or close to the skin depth of electromagnetic wave. Below that, the polarizing effect vanishes, above that the transmission decreases. In the case of aluminium the skin depth is ≈5 nm at the probe wavelength (λ=1532 nm), however the measured thicknesses (30±5 nm) are several times larger than that. The high precision optimization of the process by computer simulations [6,7] is far beyound the aims of this experimental study. The aim of this work was to demonstrate that the wire gratings produced by the presented two-step method can operate as a polarizer structure. Further experimental optimization of the evaporation (film thickness, angle of incidence, material, etc.) could be a straightforward opportunity to increase the polarization efficiency and transmission at the same time.

Summary

We demonstrated that the fabrication of surface relief gratings in transparent substrate by TWIN-LIBWE method and the subsequent coating of them by Ag film at grazing incidence is a promising, low-cost and relatively simple method to fabricate sub-micrometer scale metal wire gratings. The surface morphology and the distribution of the silver layer is significantly depends on the modulation depth of the gratings, which must be at least 15-20 nm to create individual Ag stripes with filling factor of 0.77-0.61, depending on the period.

Acknowledgments and Appendixes

The authors gratefully acknowledge the financial sup-port of Hungarian Scientific Research Fund (OTKA PD

104477). This research was supported by the European Union and the State of Hungary, co-financed by the European Social Fund in the framework of TÁMOP 4.2.4. A/2-11-1-2012-0001 ‘National Excellence Program. The project was subsidized by the European Union and co-financed by the European Social Fund. The project was partially funded by „TÁMOP-4.2.2.A-11/1/KONV-2012-0060 – „Pulse lasers for use in materials science and biophotonics” is supported by the European Union and co-financed by the European Social Fund.

References

[1] L. Zhang, C. Li, J. Li, F. Zhang and L. Shi: J. Optoelectron Adv. M., Vol. 8, Iss.2, (2006) 847.
[2] J.B. Young, H. A. Graham and E. W. Peterson: Appl. Opt. 4, (1965) 1023.
[3] M. Xu, H.P. Urbach, D.K.G de Boer, and H.J. Cornelissen: Opt. Exp., Vol. 23, No. 7, (2005) 2303.
[4] K. Knop: Opt. Com., Vol. 26, No. 3, (1978) 281.
[5] R. Petit: “Electromagnetic theory of gratings” ed. By R. Petit (Springer, Berlin, 1980)
[6] J. Chandezon, D. Maystre, and G. Raoult: J. Opt. 11, (1985) 235.
[7] J.B. Judkins and R.W. Ziolkovski: J. Opt. Soc. Am. A 12, (1995) 1974.
[8] A. E. Costley, K. H. Hursey, G. F. Neill, and J. M. Ward: JOSA, Vol. 67, Iss. 7, (1977) 979.
[9] J. P. Auton: Appl. Opt., Vol. 6, (1967) 1023.
[10] J. J. Wang, W. Zhang, X. Deng, J. Deng, F. Liu, P. Sciortino, and L. Chen: Opt. Lett., Vol. 30, Iss. 2, (2005) 195.
[11] J. Wu, C. Zhou, H. Cao and A. Hu: Opt. Laser Tech., 47, (2013) 166.
[12] L. Chen, J. J. Wang, F. Walters, X. Deng, M. Buonanno, S. Tai and X. Liu: Appl. Phys. Lett. 90, (2007) 063111.
[13] J. J. Wang, L. Chen, X. Liu, P. Sciortino, F. Liu, F. Walters and X. Deng: Appl. Phys. Lett. 89, (2006) 141105.
[14] L. Zhang, C. Li, J. LI, F. Zhang and L. Shi: JOEAM, Vol. 8, No. 2, (2006) 847.
[15] Cs. Vass, K. Osvay, T. Véső and B. Hopp: Appl Phys A-Mater, 93, (2008) 69.
[16] B. Kiss, F. Ujhelyi, A. Sipos, B. Farkas, P. Dombi, K. Osvay and Cs. Vass: JLMN, Vol. 8, No. 3, (2013) 271.
[17] B. Kiss, R. Flender and Cs. Vass: JLMN, Vol. 8, No. 3, (2013) 287.

(Received: July 18, 2014, Accepted: December 16, 2014)