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Ablated gratings on borosilicate glass by 193nm excimer laser radiation

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Abstract

Relief gratings of 500nm period have been fabricated on Er/Yb-doped borosilicate glass substrates by laser ablation using an excimer laser at a wavelength of 193nm and a modified Mach-Zehnder interferometer. The grating fabrication process has been quantified using diffraction efficiency measurements and atomic force microscope microscans, and related to the incident energy density.

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INTRODUCTION

Studies of the interaction between glass and intense UV radiation have prompted the use of 193nm excimer laser micro-machining as a reliable and effective fabrication technique for sub-micron structures [1-3], and relief gratings in particular. It has been found that glass ablation using a 193nm excimer laser produces structures of high smoothness without generating extensive surface damage in the form of cracks, in contrast to the effects of ablation at longer wavelengths. High-quality relief gratings on the surface of dielectric waveguides may play a significant role in integrated optics, particularly in the context of devices for wavelength-division multiplexed (WDM) optical fibre systems [4]. Significant benefits of relief gratings compared to UV-written index gratings, are their easy application to the majority of optical materials, their excellent temperature stability and the absence of any significant ageing problems. Relief gratings fabricated using UV ablation have been reported on polymer [5] and silicon [6] substrates using other exposure wavelengths and experimental configurations [2].

In this paper we report the fabrication of relief gratings on Er/Yb co-doped borosilicate glass using holographic ablation, with an excimer laser at a wavelength of 193nm, under atmospheric pressure conditions. A significant advantage of grating imprinting using interferometric ablation instead of other excimer laser ablation techniques is the ready tunability of the recorded grating period by straightforward adjustment of the interferometer. The borosilicate glass chosen as a substrate material has been employed in optical telecommunication applications as a host for waveguide amplifiers [7] and lasers [8]. Writing of gratings on bulk glass samples was a preliminary step to characterise the ablation process for future work on optical waveguide filters. The principal fabrication studies concerned Bragg gratings with a period near 500nm for potential application to sources in the 1.5μm wavelength band.

1 EXPERIMENTAL

The glass substrates (50 x 50 x 3mm) prepared by Corning Europe, were optically polished and had a composition of approximately 63wt% SiO_2, 10wt% B_2O_3, 9wt% Na_2O, 7wt% K_2O, 2wt% BaO, 5wt%Yb_2O_3, 3wt% Er_2O_3, and 1wt% trace compounds.

The apparatus used to expose the substrates to the radiation is shown in Figure 1. A line-narrowed injection cavity excimer laser (1) operating at a wavelength of 193nm (Lambda Physik EMG 150) was set up to produce coherent pulses of approximately 120mJ energy and FWHM duration 22ns. A three-mirror interferometer (3) was used to create a UV interference pattern on the sample surface (5). A fused silica plate (4) was placed in one of the beam paths to achieve optical path compensation. A two-lens cylindrical telescope (2) was used to allow the beam area on the sample to be adjusted. The three-mirror approach was used to avoid wavefront inversion at the sample, which is necessary since the excimer laser beam has low spatial coherence. The resulting exposure contrast was approximately 0.95. The experimental apparatus was laid out on a vibration-isolated table and placed in a sealed box in order to reduce the effects of air currents.

A series of gratings was written with varying pulse energy densities, using single, five, ten and twenty pulse exposures, at a repetition rate of 0.5Hz. The excimer laser beam was focused onto an area of typically 250μm x 1.3cm on the glass surface producing interference fringes with a periodicity of 500nm. The laser beam was not homogenized as this would significantly reduce the spatial coherence of the beam, resulting in poorer grating recording.

The gratings etched on the substrates were characterized using diffraction efficiency and atomic-force microscopy (AFM) measurements. The apparatus for diffraction efficiency measurements is described in detail elsewhere [9]. Briefly, a 633nm He-Ne probe beam was focused on the grating area using a 10x objective lens, and the first diffracted order was collected and directed to a detector employing a second 10x objective at a tilted plane. Grating depths were calculated using simple diffraction theory assuming a collimated incident beam. While this approach results in an underestimate of grating depth, due to the divergent input beam, relative grating depth estimates may be obtained. Scanning electron microscopy (SEM) was also used to study the surface structure of the gratings.

2 RESULTS AND DISCUSSION

The average grating depth for single and multi-pulse exposures, calculated using diffraction efficiency measurements, are plotted against energy density in Figures 2 and 3, respectively. For single and 5-pulse exposures the grating growth increases with the energy density. In the case of gratings formed by 10- and 20-pulse exposures, a maximum in the curves of grating depth against energy density appears for energy densities not far above the ablation threshold. The reduction in grating strength for higher energy densities may result from accumulated material damage due to the increased exposure. For multi-pulse (five, ten and twenty pulse) exposed gratings higher diffraction orders are also observed.

A cross-section of the grating grooves obtained by AFM is shown in Figure 4. For these exposures maximum grating depths of up to 130nm have been measured employing AFM scans. The large deviation from the depth estimated using diffraction efficiency measurements is due to the use of divergent beams [9]. However, the optical measurements are able to provide an estimated average grating depth over a larger ablated area, useful for simple comparison of grating writing conditions. The measured grating period, deduced from the AFM scan, was found to be 494±8nm, in good agreement with the initial design value of 500nm. A SEM micrograph of a 500nm grating is presented in Figure 5.

Non-interferometric glass ablation over large areas has been studied extensively and all proposed models relate thermal and photo-dissociation effects to the photon energy and density. These mechanisms also dominate borosilicate glass ablation, and their effects over the ablation process becomes more evident when micromachining very small features. The data presented above indicate that control over these mechanisms may be performed by altering the energy density or the number of pulses employed in the exposure. Controlling these parameters also affects other characteristics such as debris deposition or the appearance of higher spatial diffraction orders.

It is believed that the grating strength does not continue to grow with higher energy densities due to incubation effects and thermal diffusion, where exposure during earlier pulses damages the glass and alters the ablation threshold for subsequent pulses. The high contrast of the interferometric fringes, minimizes the possibility of ablation from the "dark" lines as well as from the "bright" lines of the pattern. Changes in the interference pattern due to surface modification while material is removed may result in alterations of the energy density over the grating length, affecting the grating growth. The present results indicate that 10 pulses of energy density 0.6J/cm^2 result in deep gratings of high quality at periods near 500nm in this glass.

3 SUMMARY

Direct etching of relief gratings in Er/Yb-doped borosilicate glass using interferometric 193nm excimer laser ablation is reported. The grating ablation process was studied as a function of energy fluence and number of pulses, and gratings of maximum depth 130nm having periods close to 500nm were achieved. The sensitivity of the grating ablation process to the machining conditions is described and optimum fabrication conditions for surface gratings are proposed.

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5 FIGURE CAPTIONS

1. Excimer laser ablation interferometer

2. Average grating depth vs energy density, for ablated gratings fabricated using single-pulse exposure. Point A: Single pulse ablation threshold. At low energy densities high damage volume gratings comparable to to Type II gratings [10] could be distinguished from shallow relief gratings on the exposed material.

3. Average grating depth vs average energy density, for ablated gratings fabricated using multi-pulse exposures. a: 5 pulses, b: 10 pulses, c: 20 pulses,. The lines are solely an aid to observe the trends, and do not represent a numerical fit.

4. Typical atomic force microscope cross-section of an ablated grating.

5. SEM image of excimer laser ablated grating fabricated using a five-pulse exposure and an average energy density of 0.55J/cm^2.

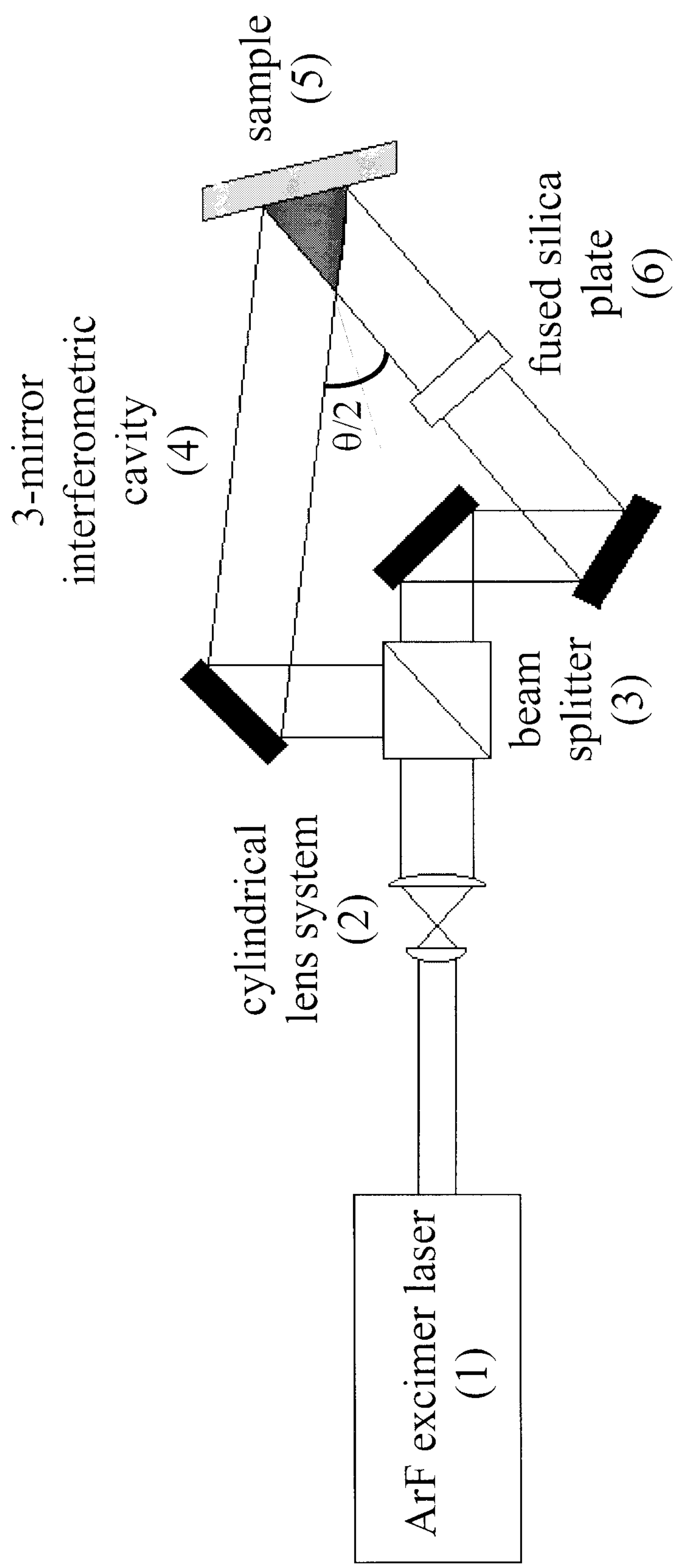
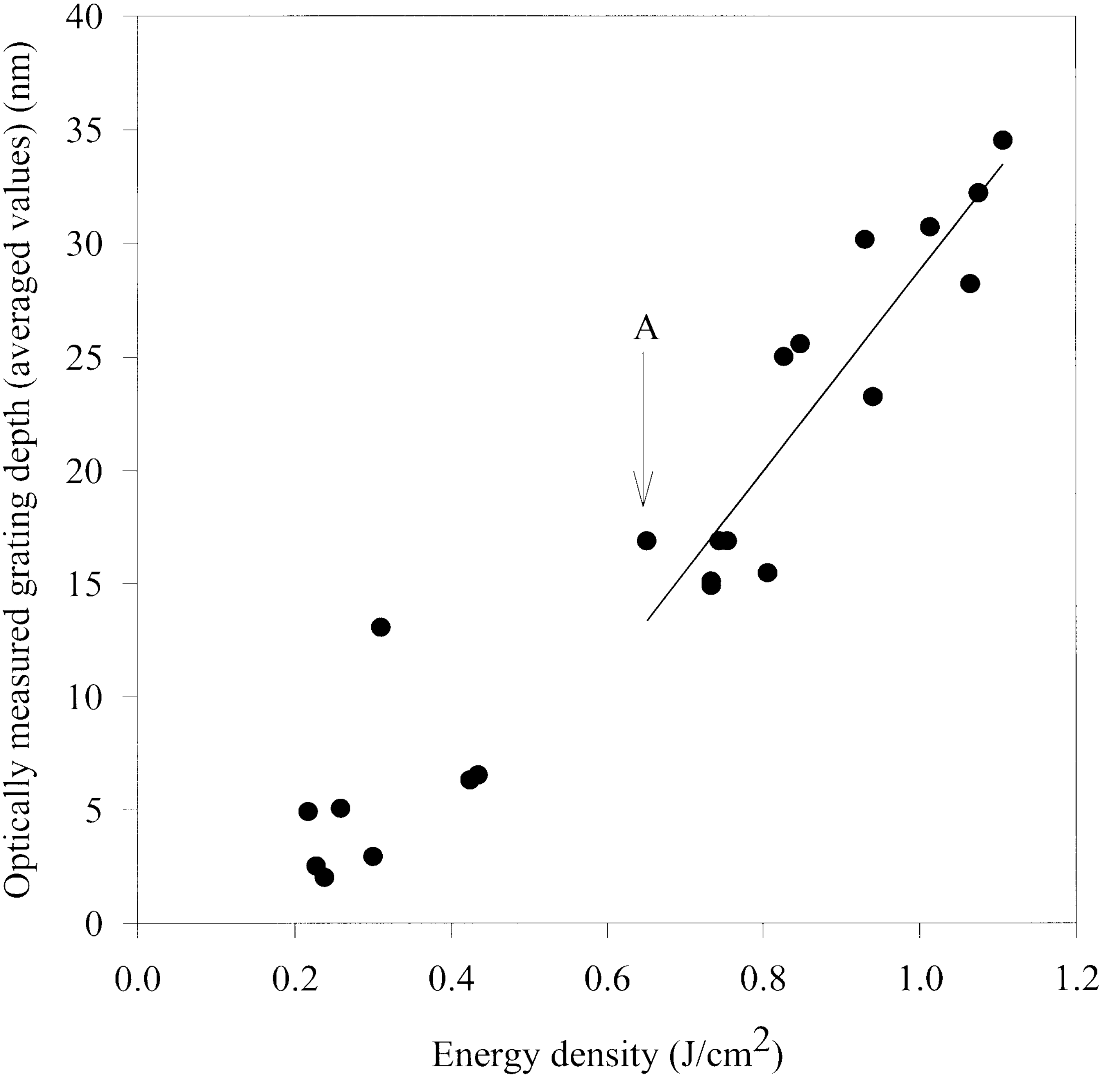

ArF excimer laser
(1)
cylindrical
lens system
(2)
beam
splitter
(3)
3-mirror
interferometric
cavity
(4)
θ/2
sample
(5)
fused silica
plate
(6)

Fig. 1



Optically measured grating depth (averaged values) (nm)
40
35
30
25
20
15
10
5
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Energy density (J/cm2)
A

Fig. 2

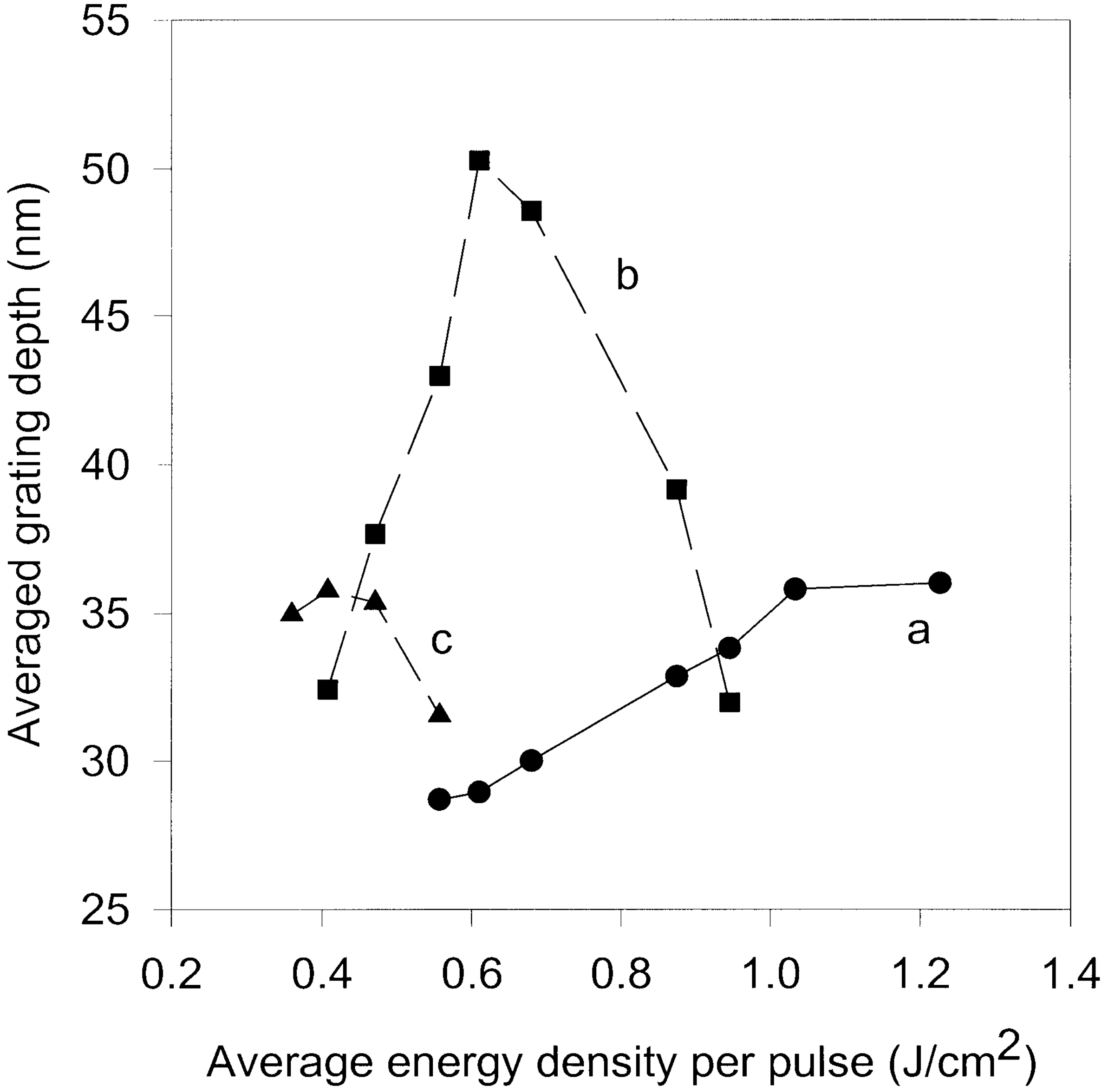

Averaged grating depth (nm)
55
50
45
40
35
30
25
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Average energy density per pulse (J/cm2)
a
b
c

Fig. 3

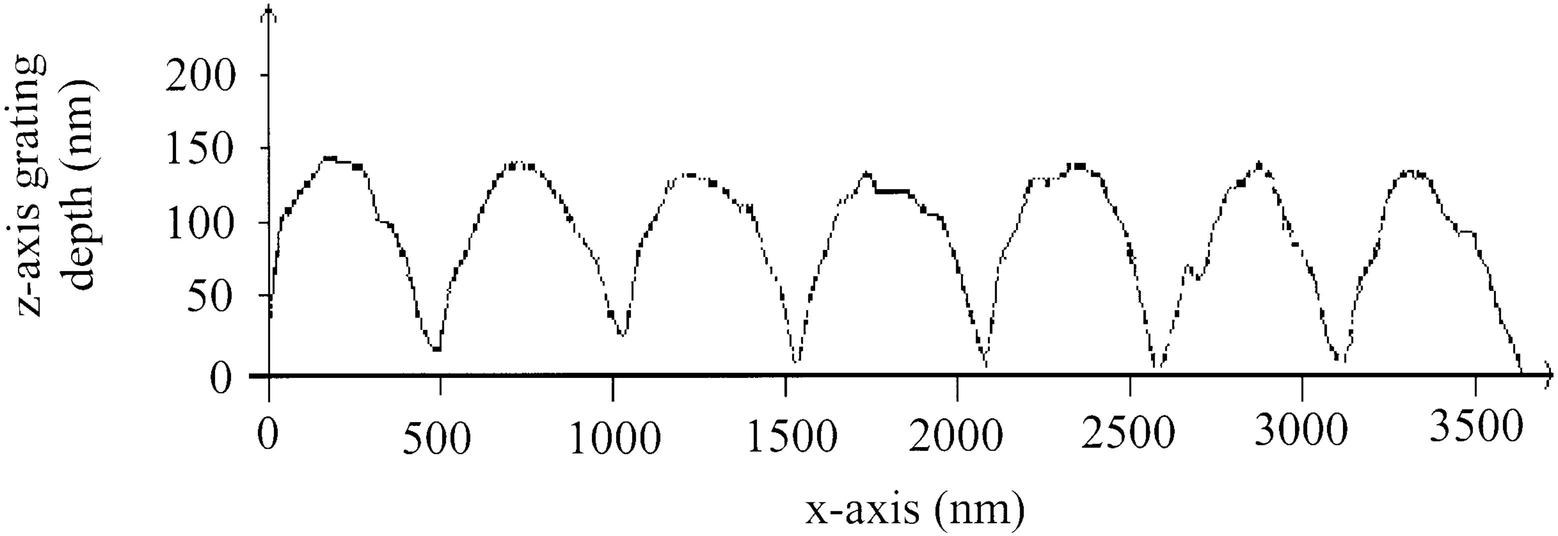

z-axis grating depth (nm)
200
150
100
50
0
0
500
1000
1500
2000
2500
3000
3500
x-axis (nm)

Fig. 4

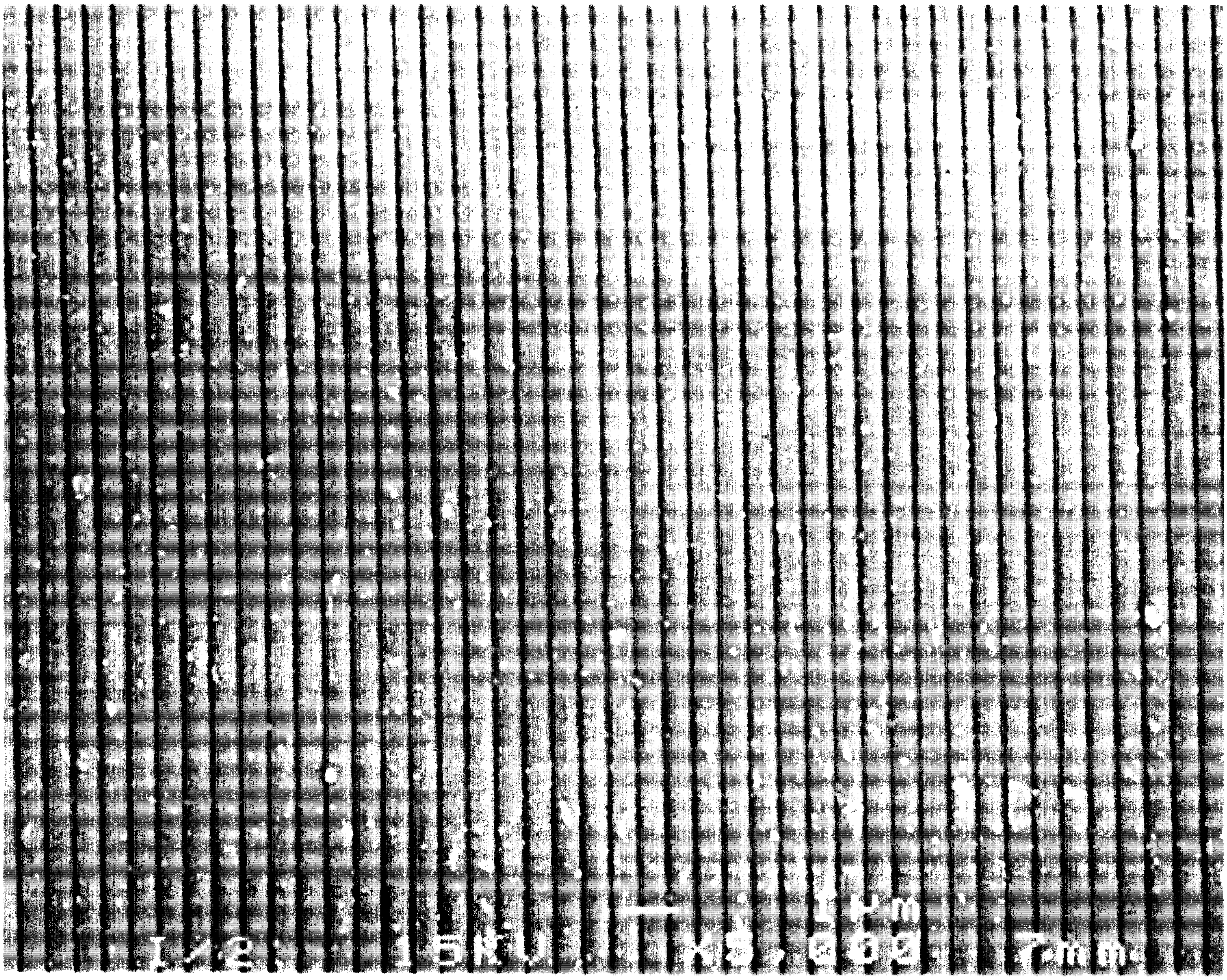


Fig.5