Fabrication of nanoscale gratings with reduced line edge roughness using nanoimprint lithography

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Line edge roughness is an important factor contributing to the problem of performance degradation in various nanoscale devices. We have developed two smoothing techniques based on nanoimprint lithography for the fabrication of nanoscale gratings with significantly reduced line edge roughness. Compared with other smoothing techniques reported before, our methods are low-cost, effective, and easy to implement. These technologies have been used for the fabrication of smooth nanochannels for stretching and separating double-stranded DNA molecules. They are also compatible with a wide range of materials and applications, including subwavelength optics, bioanalysis and micro/nano-fluidic systems. © 2003 American Vacuum Society.

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I. INTRODUCTION

Nanoscale gratings and wires have many important applications in optics, electronics, biotechnology, and micro/nano-fluidic devices and systems. In those applications, line edge roughness is an important issue that needs to be carefully addressed. Studies have shown that line edge roughness is related to the scattering loss in waveguides, x-ray zone-plates, and other optical devices. Roughness also influences the electrical performances and electron transport through nanoscale metal wires. In bioanalysis and microfluidic systems, channel interior roughness often results in device performance degradation by introducing nonuniformities in the channel width.

Previous methods targeted at reducing sidewall roughness include anisotropic wet-etch, thermal oxidation of sidewalls and etch-back, and optimization of dry etching parameters. The applicability of these methods is limited because wet-etch can only be applied to certain crystalline semiconductor materials, particularly (100) and (110) silicon substrates; thermal oxidation requires high temperature processing, which is incompatible with the materials required by many applications. Most important of all, none of these approaches is aimed at reducing the edge roughness of the original resist pattern, which serves as a mask for subsequent processing and directly affects the quality of the transferred pattern.

In this article we report on two sidewall smoothing technologies based on nanoimprint lithography (NIL), which are low-cost, high throughput, sub-10 nm lithography. NIL patterns are made by physically impressing a master mold into the imprint resist (which is usually a thermal-plastic polymer that can be changed into a viscous state at elevated temperatures) heated to above the glass transition temperature of the polymer and then releasing the mold at a lower temperature, thus duplicating the pattern in the resist.

Compared with other roughness reduction technologies, our approach directly removes the line edge roughness in the resist pattern. It is simple and does not require high temperature processing, and can be applied to a variety of substrates and materials. Using these technologies, we have fabricated highly smooth nanoscale gratings and channels that have been used in a nanofluidic device for stretching and separating double-stranded deoxyribonucleic acid (DNA) molecules. These smoothing technologies can also be applied to the fabrication of waveguides and subwavelength optical elements with reduced scattering loss and improved efficiency.

II. FABRICATION

The 200 nm period gratings used in this study were first generated using interference lithography with a single mode Ar ion laser operating at a wavelength of 351.1 nm as the light source. Nanoscale gratings patterned using interference lithography typically have rough sidewalls, which are caused by instability and fluctuation in the exposure system, limited resolution of the photoresist, and polymer aggregates.

Because NIL is a sub-10 nm lithography, line edge roughness in the master mold will also be duplicated in the resist. So the first technique is aimed at reducing sidewall roughness of the master grating. Figure 1 is a schematic of the process for the fabrication of smooth-edged grating molds. Instead of a (100) Si substrate, a (110) Si substrate is used as the mold substrate. A layer of 60 nm thick oxide was then thermally grown on the (110) Si substrate. The gratings were carefully aligned parallel to the (111) reference flat during interference lithography and were later transferred into the oxide layer using a CHF$_3$/O$_2$ reactive ion etching (RIE) process. A KOH:deionized water:isopropyl alcohol anisotropic wet-etch was used to further transfer the grating into the underlying (110) Si substrate, with the oxide serving as an etching mask. The alignment of the grating ensures that the resulting etch sidewalls terminate on (111) planes. Because the etching rate in the (111) direc-
tion is much slower than the etching rates in the ⟨100⟩ and ⟨110⟩ directions, this highly anisotropic process creates a Si grating with extremely smooth sidewalls.\textsuperscript{10}

It should be pointed out that in practice it is impossible to get the grating perfectly aligned with a crystallographic axis, experimental and theoretical studies indicate that small misalignment could result in atomic-scale steps on the etched surfaces.\textsuperscript{10} However, those atomic-scale steps are beyond the resolution of our scanning electron microscope (SEM) and will not affect the performance of the devices discussed in this article in a significant way.

Figure 2 shows the effect of this anisotropic etching process, although the original grating in the oxide shows a high degree of edge roughness, this raggedness is not reproduced in the underlying Si grating sidewalls. Finally, the oxide mask was removed using a buffered HF wet-etch (Fig. 3).

Grating patterns are duplicated using those Si surface relief gratings as master molds. Figure 4(a) shows a top view of a grating in NP-60 resist (which is an in-house developed polymethylmethacrylate-based polymer) after imprinting using the smooth-edged Si mold, and Fig. 4(b) shows the resist profile. The resist grating has vertical and smooth sidewalls, which are desirable characteristics not easily achievable using interference lithography.

The second technology takes advantage of the imprint resist, which becomes viscous when heated above its glass transition temperature ($T_g$).\textsuperscript{7} Figure 5 is a schematic of this smoothing process. The grating mold is patterned using interference lithography, which has rough sidewalls. After imprinting, a grating with rough edges was reproduced in the
imprint resist. Then an O₂ RIE process was carried out to remove the remaining resist in the recessed region and to isolate the neighboring lines from each other. After RIE, the sample was heated so the resist becomes viscous again. Because a smooth surface is energetically favorable, this thermal treatment will result in a resist pattern with a rounded profile and significantly reduced surface roughness.

Figure 6 shows the effect of thermal annealing on the edge roughness. In this experiment we used the in-house developed imprint resist NP-60, which has a $T_g$ of 100 °C. Figure 6(a) is the top view of the resist grating after imprinting using a rough-edged grating mold. The sample was then baked at 100 °C on a hot-plate for 10 min. Figure 6(b) shows a top view of the resist pattern with smooth sidewalls after the thermal treatment.

III. APPLICATIONS

Using these NIL-based line edge roughness reduction techniques, we have successfully fabricated nanoscale gratings over a large area (4 in. wafer) on various substrates. The smallest grating pitch achievable is around 190 nm, which is determined by the wavelength of the laser (351.1 nm) used in interference lithography.

These nanoscale gratings with smooth sidewalls have many important applications, including subwavelength optics, micro/nano-fluidic devices, and bioanalysis for the manipulation of single biological molecules.

In subwavelength optical applications, because transmission loss increases as the second exponential of roughness¹ as light propagates inside the gratings, smoothing technologies can be used for the fabrication of highly efficient subwavelength devices.

Recently we have fabricated and demonstrated a fluidic device consisting of sealed nanochannels so that double-stranded DNA molecules can be stretched and moved along these channels.⁸ Fabrication of highly smooth gratings is a critical step in this application because sidewall roughness causes nonuniform stretching of the DNA molecules and could even block the movement of the DNA, due to the small dimensions (<100 nm) of these channels.

IV. CONCLUSION

In conclusion, we have developed sidewall-smoothing technologies based on nanoimprint lithography. Using these techniques, we have fabricated nanogratings with extremely smooth sidewalls over a large area. Compared with other sidewall smoothing technologies, ours are low-cost, effective, and can be applied to a variety of materials and substrates. These smooth gratings have a variety of applications in optics, micro/nano-fluidic devices, and biotechnology.

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