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Focussed ion beam fabrication of large and complex nanopatterns

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The fabrication of nanopatterns with a focussed ion beam (FIB) has recently been expanded to more complex nanopatterns with large numbers of individual pattern elements and covering larger pattern areas. We present two examples of FIB-fabricated large and complex nanopatterns and describe the key aspects of the underlying process automation. The FIB-fabrication has been carried out on DualBeam^{TM} instruments, which combine the FIB with a scanning electron microscope in one single instrument. We also present examples on how FIB-cross-sectioning and high-resolution electron microscopy can be applied to characterise the just fabricated nanopatterns in great detail.

Keywords: DualBeam^{TM}; nanopatterning; nanoprototyping; nanofabrication; FIB

1. Introduction

The capabilities of a focussed ion beam (FIB) to directly remove or deposit material with accuracies of a few nanometres and the ability to observe these patterning processes live with a scanning electron microscope (SEM) in DualBeam^{TM} instruments are attracting an increasing number of nanoprototyping applications across a wide range of use cases. The majority of applications to date have aimed at achieving the smallest possible feature sizes for groups of a few small pattern elements. Modern FIB-column technology has not only reduced the minimum spot size, pushing to smaller nanodevice dimensions, but has also led to improved beam profiles at large and intermediate FIB currents. The FIBs with high beam currents and yet small spot sizes and narrow profiles are opening novel opportunities to expand FIB prototyping to larger areas of complex shapes. The better understanding of the FIB-patterning process [1] has led to the development of optimised strategies for FIB-patterning; redeposition artefacts are minimised and a tighter control of pattern dimensions are achieved by executing groups of pattern elements in parallel with many repeated passes and the pattern depth is controlled through material dependent sputter rate libraries. These FIB strategies have been incorporated into process automation (NanoBuilder^{TM}) and are combined with FIB-optimised alignment mark recognition for accurate pattern placement.

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2. Photonic crystals

The direct fabrication of photonic crystals with a DualBeam™ instrument offers the unique opportunity that photonic devices can sequentially be added to a pre-patterned wafer such that each device can thoroughly be characterised directly after the patterning step. The outcome of the device characterisation can then immediately be used for design modifications or process optimisation for the next device. Nanofabrication with an FIB does not require any conventional nanofabrication processes, such as resist coating, plasma etching or batch deposition, which means that all devices outside the FIB-patterning area will remain unaffected. Hence, nanoprototyping with a DualBeam™ instrument allows much shorter iteration cycles in a development process with the potential to cut costs, or allows accommodating an extended scope of work within the given time frame of a research project.

Figure 1 shows an FIB milled nanophotonic structure in an InP substrate. The pattern encompasses a total area of $480 \times 100\,\mu m^2$ with a photonic crystal structure consisting of 220 nm holes in a hexagonal unit cell. For practical reasons the total area has been divided into six sections which are executed one after the other. The patterning time for each section can this way be kept short enough to keep the impact of any drift at a minimum and the writing fields can be kept small enough to ensure best linearity and uniformity across the entire pattern area.

Dividing a photonic crystal into sections requires a stitching accuracy at the section borders that avoids any discontinuity of the periodic pattern which would disturb the functionality of the photonic crystal. Working with an FIB does provide in this case the unique benefit that alignment marks can be milled as part of the pattern in each field.

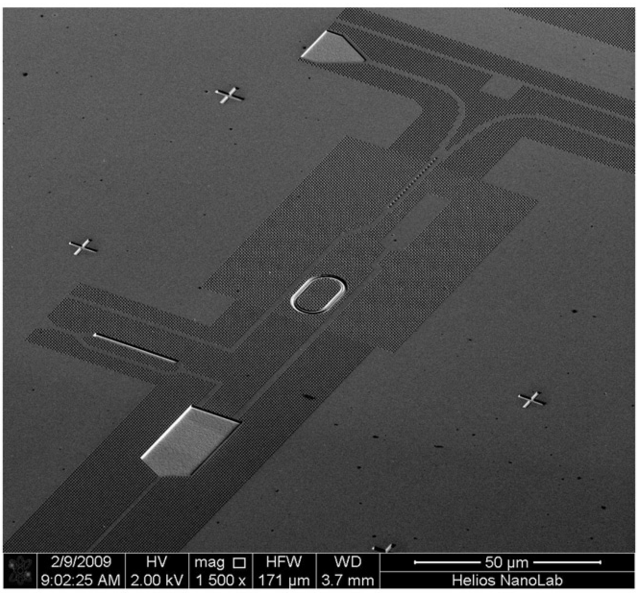

Figure 1. A nanophotonic proof-of-concept structure in an InP substrate. The total pattern area of $480 \times 100\,\mu m^2$ was FIB milled in 1 h and 27 min.

Since the alignment marks are directly patterned, not requiring any development as in other lithography techniques, they can directly be used for alignment and pattern placement of the subsequent field. The cross-shaped alignment marks are visible in Figure 1. The mark recognition is performed by means of measuring the detector signal while the ion beam is scanning in a line across an alignment mark. The intensity profile of two perpendicular lines is sufficient to determine the exact position of the alignment mark. Using alignment for stitching enables reducing stitching errors even below the mechanical tolerances of high precision piezo-stages. Figure 2 shows the boundary of two adjacent writing fields of the photonic crystal in Figure 1. Stitching errors smaller than 60 nm were measured for field-to-field stitching of 200 μm writing fields.

An additional advantage of a DualBeam system is the capability to cut a cross-section into the fabricated pattern exactly at the axis of any individual hole of the photonic crystal structure and gain information over pattern depth and profiles, and still retain the functionality of the device. Figure 3 shows the photonic crystal with an FIB cross-section at the outermost row of holes at a safe distance from the waveguide at the top of the image.

The cross-sectional image in Figure 4 shows the depth and the profile of the holes of the photonic crystal; it also shows the roughness of sidewall inside a high aspect ratio hole. Gas assisted FIB etching techniques with sacrificial surface layers have been reported to produce even higher aspect ratios for FIB made photonic crystals in InP substrate [2].

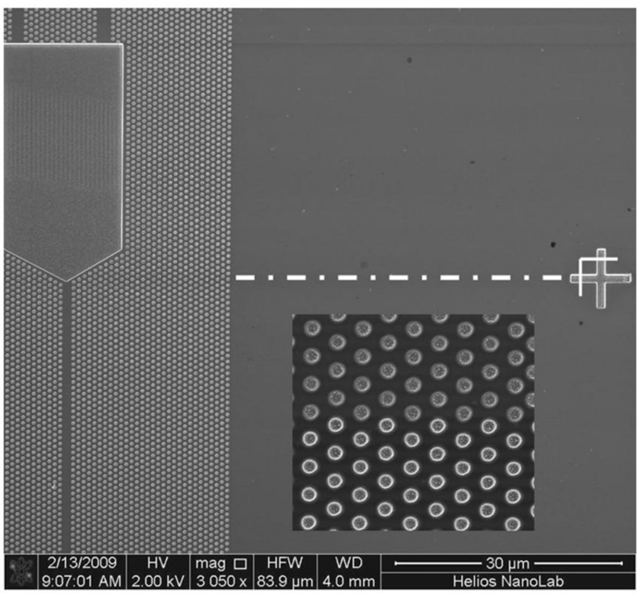

Figure 2. The photonic crystal at the boundary of two writing fields. One of the alignment crosses is visible on the right-hand side. The dashed line guide the eye to the stitching position in the photonic crystal. The two white lines on the alignment mark indicate the positions of the respective line scans for the mark recognition. The FIB line scans do not cause any visible damage to the alignment marks and avoid any unwanted ion exposure of the substrate. The enlarged inset shows the stitch line at higher magnification (contrast difference due to redeposition).

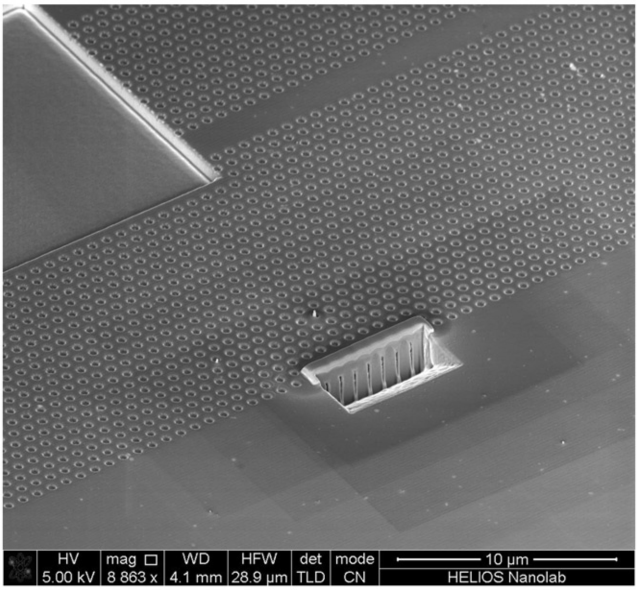

Figure 3. An FIB cross-section at the edge of the photonic crystal provides information over pattern depth and profile.

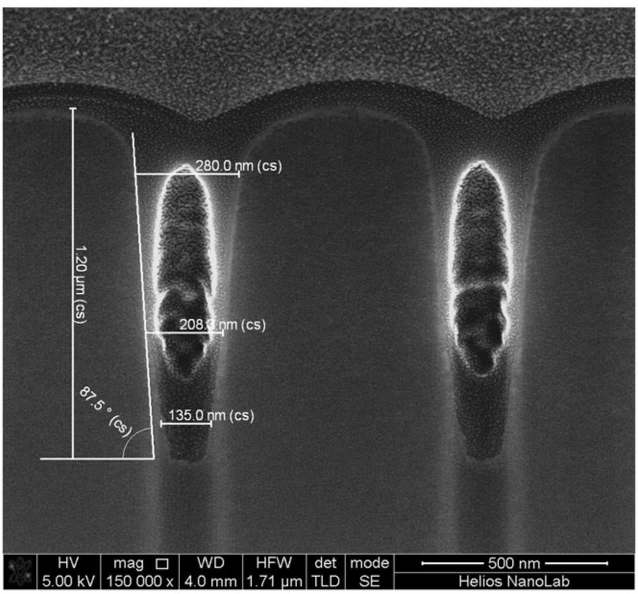

Figure 4. An SEM image of the FIB-cross-section of two holes of the photonic crystal. The grainy material inside and above the hole results from a beam induced Pt-deposition which is part of the FIB cross-section procedure. The cavities that are visible in the Pt-filling of the holes are a result of the high aspect ratio of the photonic crystal pattern.

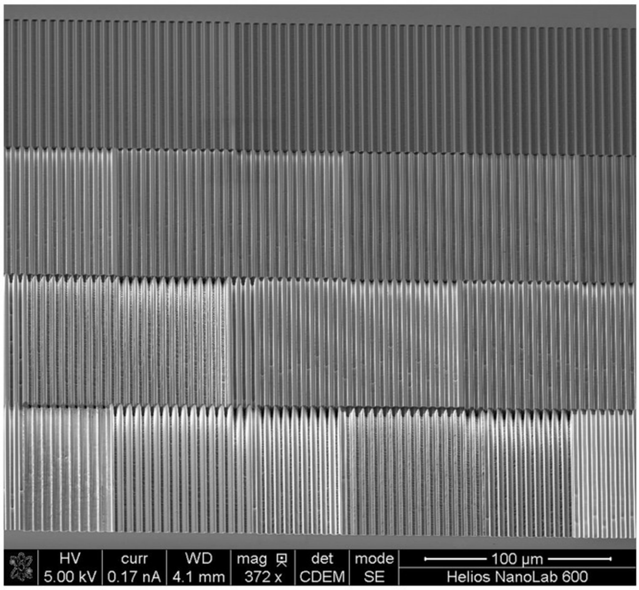

Figure 5. A diffractive optical element of a fast parallel processing spectrometer which was milled into Si with a 21 nA FIB. Trenches of $2.5 \times 125\,\mu m^2$ were starting from a depth of 35 nm to a depth of 3.5 μm in steps of 35 nm.

3. Diffractive optical element

Applications that involve pattern elements with dimensions in the tens of micrometre range have hardly been explored with FIB-patterning. The removal of relatively large material volumes with a single beam direct write approach is in general considered to be inefficient. However, the improvements of FIB columns to deliver narrower beam profiles at high beam currents together with the development of dedicated FIB pattern engines with automated drift correction combine higher patterning speeds with advanced process control for long process times. Both features enable the expansion of the range of possible applications for FIB-patterning to micromachining.

The unique capabilities of DualBeam^{TM} instruments to control not only the lateral dimensions of a given design but also the depth of each individual pattern element independently were exploited for the direct FIB machining of a diffractive optical element for a fast parallel processing spectrometer [3]. Trenches of length 125 μm and width of 2.5 μm were patterned across an area of $1 \times 0.5\,mm^2$. The central area of the trench pattern is shown in Figure 5. The trenches were arranged in groups that differ in pattern depth from 35 nm to 3.5 μm in step sizes of 35 nm. The trenches were patterned with a 21 nA FIB in a total pattern writing time of 6 h and 52 min.

While for most applications of FIB-patterning, the quality of the pattern sidewalls is decisive for a successful device, the diffractive optical element relies mainly on the flatness of the pattern bottom for good optical reflectivity. Figure 6 shows a cross-sectional image of one of the deeper trenches with a flat area parallel to the top surface at the centre of the trench bottom. The second figure of merit is the roughness of the trench bottoms which is required to be less than 10% of the wavelength of the visible spectral range. The SEM

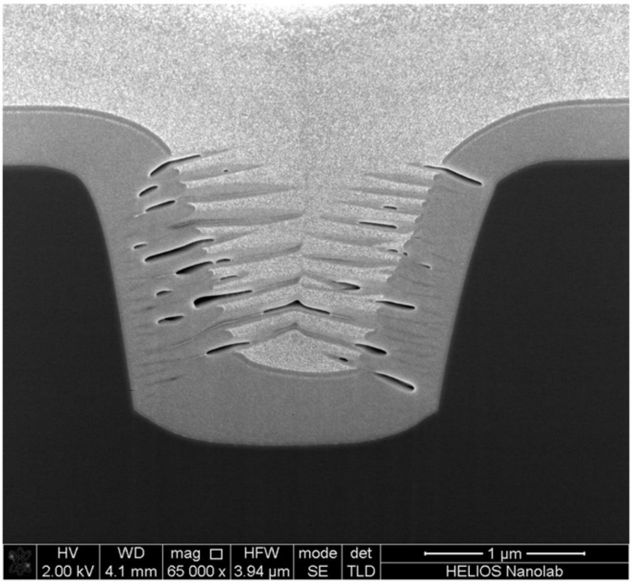

Figure 6. Cross-sectional image of one of the trenches of the diffractive optical element. The trenches were milled with a 21 nA FIB.

micrograph in Figure 7 gives an impression of the surface roughness inside the FIB patterns at the junction of two groups of shallower trenches. A quantitative measurement of the average roughness R_a of the pattern bottom was carried out with an atomic force microscope (AFM): the R_a inside the FIB pattern area was 27 nm, while the R_a of the Si wafer surface was 4 nm.

4. Summary

The advances in FIB column technology and in patterning engines specifically designed for DualBeam™ instruments have largely increased the number of possible applications that can benefit from the unique capabilities of FIB nanofabrication.

Applications that require periodic or continuous fine features across large areas, such as photonic crystals or nanofluidic devices can now be realised by using the technique of pattern alignment based on alignment marks that are written along with the actual device. There is no other lithographic process that is capable of direct recognition of alignment marks that are part of the device layer that is still being processed.

Applications that require an individual control of depth for the individual pattern elements, such as the diffractive optical element, are feasible in one single process. There is no other nanofabrication process that can etch or deposit material of different depths or heights with such a degree of control in one single process step. The total FIB-patterning time for the diffractive optical element of almost 7 h during which the DualBeam system ran unattended was also the total process time after which the device prototype was ready for optical characterisation.

The examples presented in this article show that large and complex nanopatterns can be fabricated with FIBs with a very high degree of control over lateral dimensions, depth

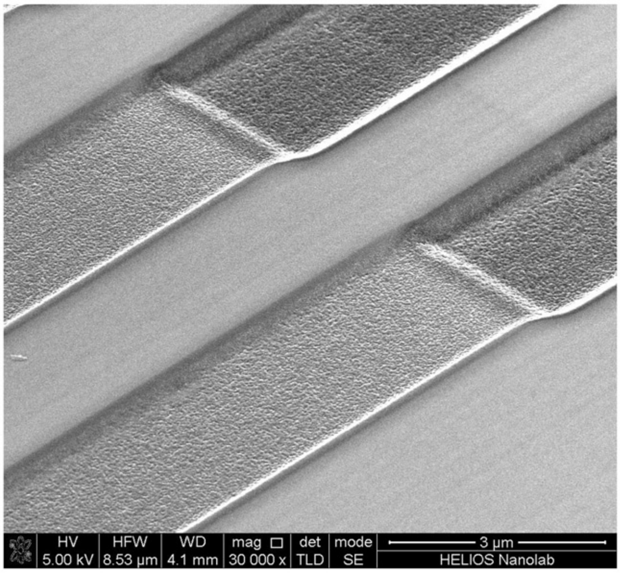

Figure 7. Junction of two groups of trenches of different depths. The difference in surface roughness between the Si wafer surface and the FIB patterned area is well visible.

or height and pattern placement beyond the boundaries of single writing fields. The beam sizes and beam shapes of FIBs in modern instruments and the automated control functions of dedicated pattern engines enable the required writing speeds and provide the necessary process control and automation.

The added benefit of a DualBeam™ instrument to measure, inspect and characterise the resulting patterns with ultra high resolution has been demonstrated with the SEM images of substrate surfaces and FIB cross-sections. Having all this patterning and inspection functionality available in one single instrument is a strong base for successful and truly rapid nanoprototyping.

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