

Focused Ion Beam fabrication of large and complex nanopatterns

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ABSTRACT

The capabilities of a focused ion beam (FIB) to directly remove or deposit material with accuracies of a few nanometers and the ability to observe these patterning processes live with a scanning electron microscope (SEM) in DualBeam™ 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. Focused ion beams 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 adequate strategies for FIB patterning [1] has led to the development of optimized strategies for FIB patterning and automated process control.

Keywords: dualbeam, nanopatterning, nanoprototyping, nanofabrication, fib

1 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 characterized directly after the patterning step. The outcome of the device characterization can then immediately be used for design modifications or process optimization for the next device. Nanofabrication with a FIB does not require any conventional nanofabrication processes such as resist coating, plasma etching or batch deposition, which means that all devices in the vicinity 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 a FIB milled nanophotonic structure in an InP substrate. The pattern encompasses a total area of $480 \times 100 \mu\text{m}^2$ 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.

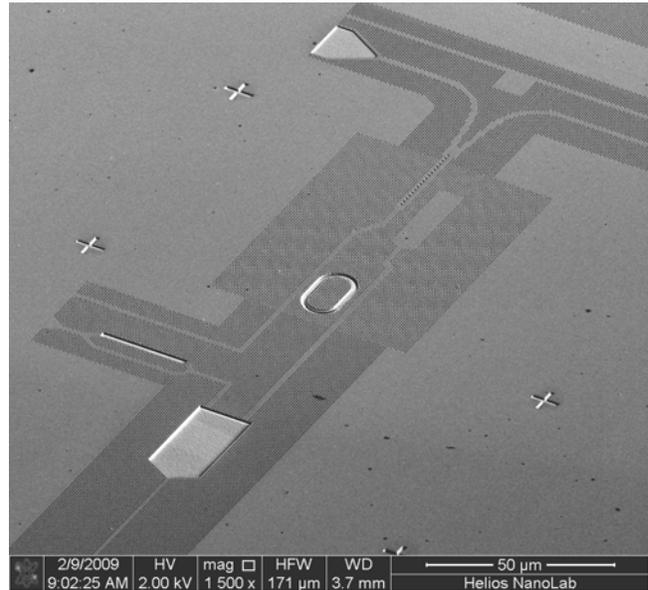


Figure 1: A nanophotonic proof-of-concept structure in an InP substrate. The total pattern area of $480 \times 100 \mu\text{m}^2$ was FIB milled in 1 hour and 27 minutes.

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 a FIB does provide in this case the unique benefit that alignment marks can be milled as part of the pattern in each field. 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. 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.

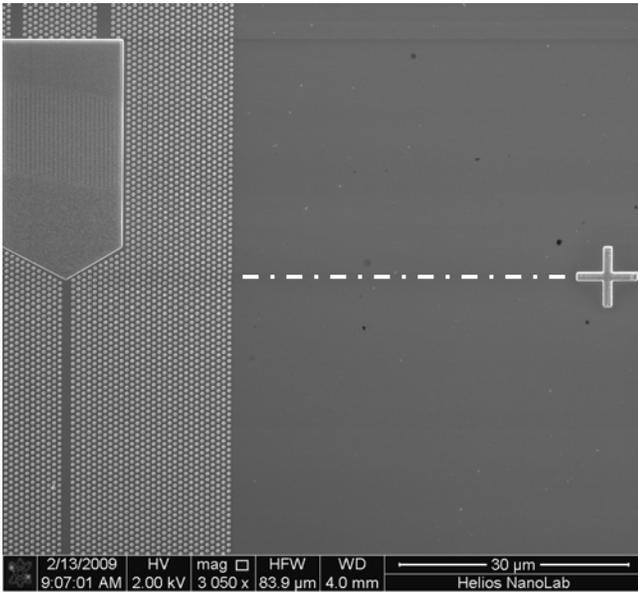


Figure 2: The photonic crystal at the boundary of two writing fields. One of the alignment crosses is visible at the right hand side. The dashed line guides the eye to the stitching position in the photonic crystal.

An additional advantage of a DualBeam system is the capability to site specifically cross-section 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 a FIB cross-section at the outermost row of holes at a safe distance from the waveguide at the top of the image.

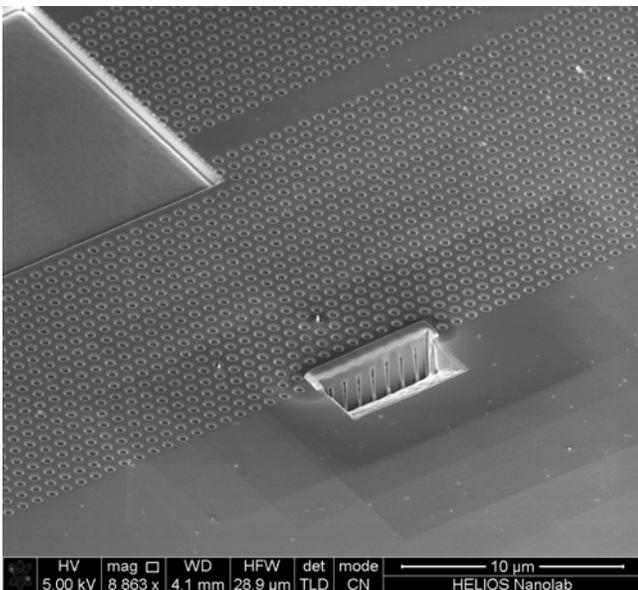


Figure 3: A FIB cross-section at the edge of the photonic crystal provides information over pattern depth and profile.

The cross-sectional image in figure 4 shows the depth and the profile of the holes of the photonic crystal; it even shows the sidewall roughness 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 [2].

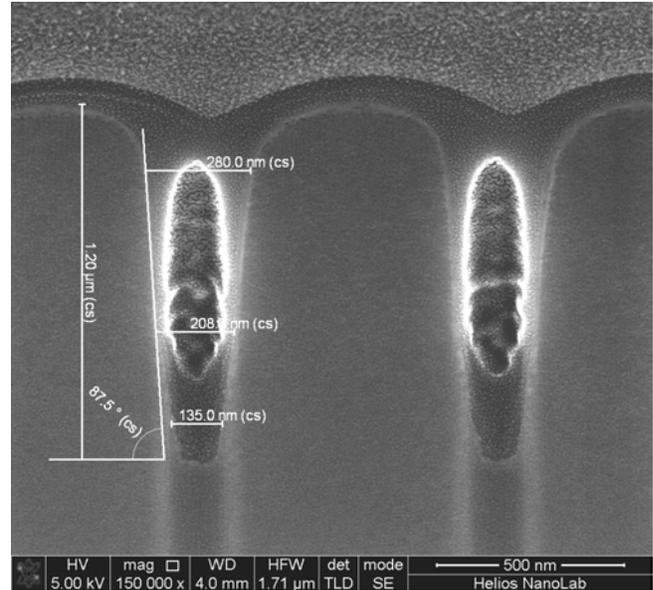


Figure 4: A SEM image of the FIB-cross-section of two holes of the photonic crystal. The grainy material inside and above the hole results from a beam induced Pt-deposition which is part of the FIB cross-section procedure. The cavities that are visible in the Pt-filling of the holes are a result of the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

2 DIFFRACTIVE OPTICAL ELEMENT

Applications that involve pattern elements with dimensions in the tens of micrometer 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 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 125 μm length and 2.5 μm

width were patterned across an area of $1 \times 0.5 \text{ mm}^2$. The central area of the trench pattern is shown in figure 5. The trenches are 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 hours 52 minutes.

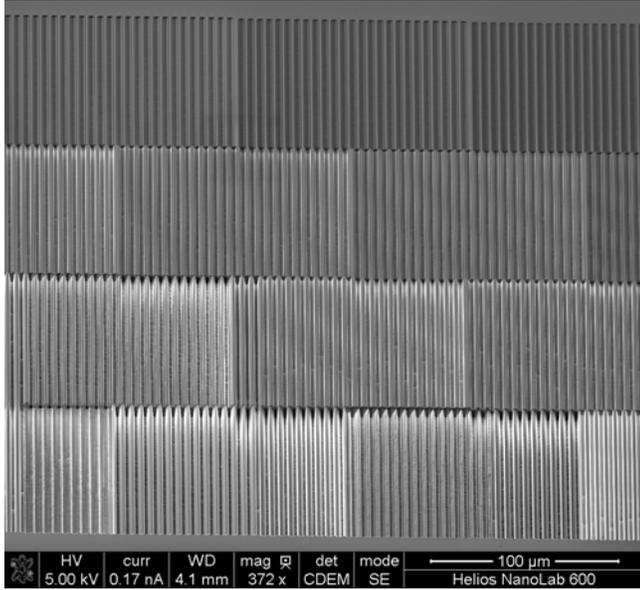


Figure 5: A diffractive optical element of a fast parallel processing spectrometer which was milled into Si with a 21-nA FIB. Trenches of $2.5 \times 125 \mu\text{m}^2$ were starting from a depth of 35 nm to a depth of 3.5 μm in steps of 35 nm.

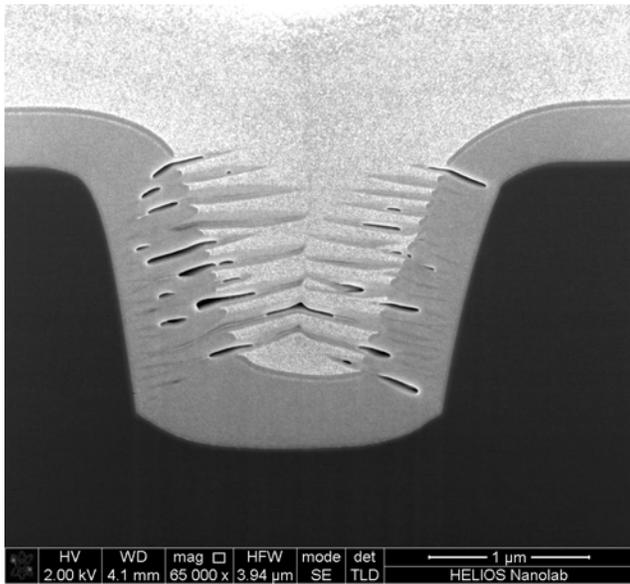


Figure 6: Cross-sectional images of one trench of the diffractive optical element. The trenches were milled with a 21-nA FIB.

While for most applications of FIB patterning, the quality of the pattern sidewalls is decisive for a successful device, does the diffractive optical element rely 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 center 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 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 AFM: the R_a inside the FIB pattern area was 27 nm, while the R_a of the Si wafer surface was 4 nm.

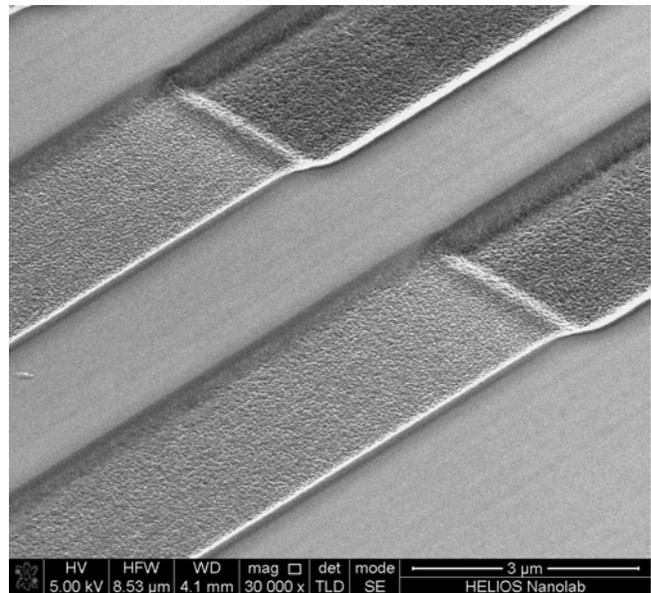


Figure 7: Junction of two groups of trenches of different depth. The difference in surface roughness between the Si wafer surface and the FIB patterned area is well visible.

3 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 realized by using the technique of pattern alignment based on alignment marks that are written along with the actual device. There is no other lithography 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 depth or height with such a degree of control in one single process step. The total FIB patterning time for the diffractive optical element of almost 7 hours during which the DualBeam system ran unattended was also the total process time after which the device prototype was ready for optical characterization.

The examples presented in this paper show that large and complex nanopatterns can be fabricated with focused ion beams with a very high degree of control over lateral dimensions, depth or height and pattern placement beyond the boundaries of single writing fields. The beam sizes and beam shapes of focused ion beams 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 DualBeam instrument to measure, inspect and characterize 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 nanoprotyping.

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