Focused ion beam etching of thin diamond layers

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Diamond, with its wide range of extreme properties, is an ideal candidate for many optical applications. Since it has become possible to grow thin layers of diamond on various substrates, the challenge of structuring these layers remains, due to the extensive chemical inertness and mechanical hardness of diamond. Focused ion beam (FIB) etching offers the opportunity to fabricate structures at a very small scale with a very short development cycle.

Introduction

Diamond is unmatched in its optical, mechanical, thermal and electrical properties. It is a very suitable material for photonics, due to its transparency from the deep ultraviolet to the far infrared, in addition to its high refractive index of 2.4 [1]. For various optical applications, the high thermal conductivity, chemical inertness, biocompatibility, high density and large Young modulus are also of great benifit.
In recent years, it has become possible to grow thin layers of synthetic diamond on a wide range of substrate materials using chemical vapour deposition (CVD) [2]. This is a key step in developing integrated optical circuits. Although there have been many attempts to create waveguides in CVD diamond [3], quantitative reports of optical losses in these waveguides have yet to be made.

Thin layers of diamond

Vertical confinement is achieved by using thin layers of diamond, surrounded by a low index material. Before it was possible to grow thin layers, bulk diamond had to be underetched to create diamond membranes that could be relocated on low index materials [4]. This method still holds the advantage of using single crystal diamond. Diamond layers that are synthetically grown on a non-diamond substrate are polycrystalline [5]. This leads to light absorption at grain bounderies and scattering at the rough surface. The fabrication of waveguides however is much more straightforward, since vertical confinement is automatically achieved by growing on a low index material.
For this work, diamond was grown by CVD at the Institute for Material Research of Hasselt University. Layers of various thicknesses (100 to 475 nm) were grown on a micron thick SiO_2-layer on top of a Si-substrate. The grain size and consequently surface roughness increase with layer thickness. Figure 1 shows the surface of the 475 nm thick sample.

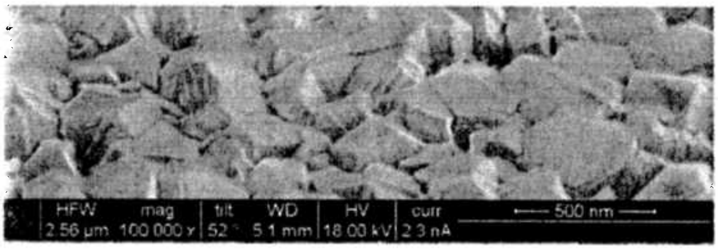

Figure 1: SEM image of the diamond surface.

Diamond waveguides

Focused ion beam milling

A beam of gallium ions is focused to a nanometer sized spot to remove the target material. By moving the beam according to a certain pattern, sub-micrometer sized structures can be produced with a precision of tens of nanometers. This precision is limited by the beam size, which is smaller when lower currents are used. During the etch process, gallium ions will be implanted in the target material, causing additional losses through absorption.
In addition to milling, high resolution images can be made by scanning the entire field of view and recording the secondary electrons for each pixel. One should note that taking an image is exactly the same as etching a rectangle. This means some material will be removed and gallium ions will be implanted.
At any given magnification, the number of points that can be addressed individually is the same. Reducing the magnification (i.e. increasing the field width) will thus lead to less accurate structures. When large or long structures, such as waveguides, are required, it is necessary to etch part of the structure and move the stage to continue with the next part. This is called stitching. Since stage movements cannot be made with sub-micron accuracy, an alignment procedure is necessary.

Automated alignment procedure for stitching

To create a straight ridge waveguide, two long rectangle trenches have to be etched. Because the rectangles are rather large and etching diamond is rather slow, a relatively high current is used (7 nA). The writing field is chosen to be 100 μm. We work with a 12-bit patterning board, so the locations that are addressed individually for this writing field are about 24 nm apart. The waveguide will be built up out of 80 μm long pieces.
Using the runScript application from FEI company, an automated alignment procedure was programmed, based on image recognition. Since imaging causes damage to the sample, only some areas of the field will be imaged, avoiding unnecessary ion implantation in the waveguide.
Before starting the procedure, the scan rotation of the system is adjusted in such a way that the beam axes coincide with the stage axes. Furthermore, the magnification is adjusted for calibration purposes. Both tasks are performed automatically before starting the actual stitching procedure.
In the first step of this procedure, two trenches and alignment markers are etched. Figure 2a shows them in black. Hereafter, areas A and B are imaged and stored as reference

images. The next step is to move the stage over 80 μm and take images of areas A' and B'. In case of a perfect stage move, the two markers are exactly in the middle of these areas (shown in grey). In reality, there will be a small deviation. A matching procedure will now look for the best match with the reference images, thus determining the actual stage move. According to these results, a beam shift is introduced to correct for the stage inaccuracy and the next part is etched. Figure 2b shows a SEM image of the result of this stitching procedure. It can be repeated as often as required.

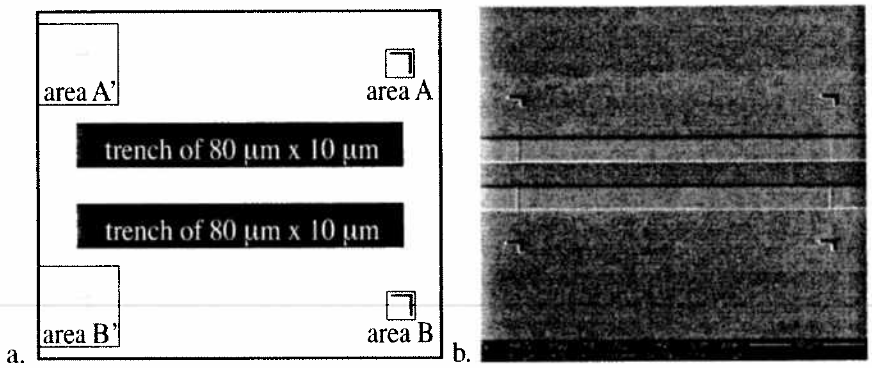

Figure 2: Automatic alignment procedure for stitching: a. scheme and b. SEM image of result. During this procedure, the black trenches and markers are etched and only the four indicated areas are imaged.

Light coupling

Both in-plane as out-of-plane coupling is possible to get light in and out of the waveguide. For in-plane coupling, the waveguide is etched from side to side of a thin sample and light is focused onto one of the facets. The outcoupled light is collected by an objective lens and measured with a power meter. It is however difficult to obtain clean cleaved facets, because the diamond layer breaks along the grain borders (figure 3a). Furthermore, this method has a very low alignment tolerance.

In silicon photonics, grating couplers are often used to couple light between optical fibres and waveguides in a vertical way [6]. The coupling efficiency is wavelength dependent and can be simulated with eigenmode expansion tools. Grating couplers were etched with FIB using a lower current (1nA), see figure 3b. Both facet coupling and grating coupling measurements were attempted, but so far, no unambiguous results could be obtained.

Conclusions

An automatic alignment procedure based on image recognition was used to stitch waveguides in thin diamond layers with FIB. FIB etching allows for a very short development cycle of nanophotonic components. Attempts to couple light by in-plane or out-of-plane coupling so far didn't result in loss figures. Further efforts will be made to improve waveguide stitching and optimize the grating design and fabrication. Furthermore, it wil be crucial to reduce surface roughness, since this is expected to cause large losses.

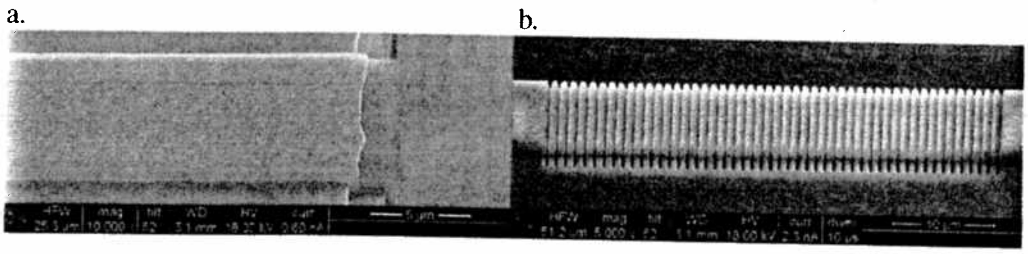

Figure 3: In-plane light coupling (a) is difficult due to poor facet quality. Out-of-plane coupling (b) can be done with grating couplers.

Acknowledgments

M. Verbist thanks the Institute for the Promotion of Innovation through Science and Technology (IWT) for a specialization grant and the Institute for Material Research (IMO) of Hasselt University for the collaboration.

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