Diamond & Related Materials 20 (2011) 556–559

Contents lists available at ScienceDirect

Diamond & Related Materials

journal homepage: www.elsevier.com/locate/diamond

Towards characterisation of millimetre length waveguides and new fabrication method for nanoscale diamond photonic structures☆☆

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ARTICLE INFO

Available online 25 February 2011

Keywords:
Diamond crystal
Reactive ion etching (RIE)
Optical properties

ABSTRACT

We present a novel approach to achieving in-plane coupling for ridge waveguides fabricated in single crystal diamond through a modification to the graphitic implant process. The etched cross-section of a diamond ridge structure is examined to confirm roughness estimates and the trenching effect. Finally nanoscale optical cavities are fabricated in polycrystalline diamond using a new method of exposure using focussed ion beam as a hard mask to pattern the structures.

1. Introduction

Diamond is emerging as an exciting material for optics due to its ability to generate single photons at room temperature through colour centres such as the nitrogen-vacancy centre (NV^-) [1] and also act as a waveguiding material [2,3]. The ongoing development of a true single photon source has applications in quantum communications and computing [4,5] and the large transparency window of diamond also makes it suitable for forming waveguides to steer these photons and thus allowing monolithic devices.

Progress has been made fabricating optical waveguides in diamond however propagation over lengths >100 μm and characterisation of attenuation have yet to be demonstrated. In order to reach these goals we seek to improve coupling to the waveguides ideally through use of in-plane coupling. To do this we have fabricated waveguides using photolithography which extend from one side of a 3 mm × 3 mm single crystal diamond to the other and modified the graphitic implant approach to suit waveguides of this length and proximity to the edge.

There is also interest in fabricating diamond optical structures with sub-micron dimensions, particularly cavities such as photonic crystals [6,7], composite GaP-diamond structures [8] or proposed slot-waveguides [9]. These structures may be used to enhance emission efficiencies of centres and potentially form qubits, building blocks for quantum information applications. We also investigate the application of a new FIB hard-mask technique [10] which gives nanometre-scale resolution using no deposited mask layer to form these structures.

2. Modified implant towards optical characterisation

To produce optical waveguides in single crystal diamond it is necessary to implement vertical confinement. This has been achieved previously through the implantation of a graphitic layer 3.5 μm beneath the surface across a section of the diamond which is to be patterned [2] or across the entire sample [3]. After fabrication of the photonic structures the graphitic layer is removed by electrochemical etching leaving the required air gap beneath the photonic structures. A limitation of these structures are that the waveguides have not extended to the edge of the sample and so required mirrors to be milled (using FIB) into the waveguides to allow light to be launched vertically into these samples. This is generally undesirable due to the loss involved.

To produce waveguides which extend over the majority of a 3 mm × 3 mm diamond (Sumitomo type 1b) surface we have used a polydimethylsiloxane (PDMS) backing to reduce the impact of edge beads i.e. the build-up of photoresist around the edges of the sample during spin-deposition [11,12]. In an initial sample, a graphitic implant across the entire sample led to a weakening of the thin diamond surface as the graphite was removed. The electrochemical etch requires lengthy etch times (days) to remove the graphite from the end of one waveguide to the other and indiscriminately etches out in all directions so that much of the surface film was released from the sample which causes cracking in subsequent handling.

To counter this, the current sample was masked during the graphitic implant which separated the implanted layer into four different diagonal sections as shown in Fig. 1. The aim is to align the masked graphitic regions with sets of waveguides so that ultimately, the graphite layer will be removed beneath each waveguide set. Diagonal strips were chosen to give waveguides of varied length. Following this the sample was patterned by photolithography (as shown in Fig. 2) and

☆☆ Presented at the Diamond 2010, 21st European Conference on Diamond, Diamond- Like Materials, Carbon Nanotubes, and Nitrides, Budapest.

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doi:10.1016/j.diamond.2011.02.013

Fig. 1. Single crystal diamond with diagonal graphitic implant. Yellow region is unimplanted region and the dark region is ion implanted region. Sample is approximately 3 mm × 3 mm in area.

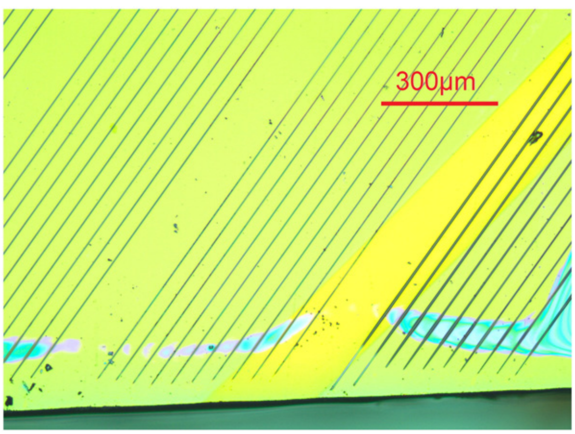

Fig. 2. Waveguides patterned in AZ6112 photoresist prior to reactive ion etching. Waveguides run close to edge although some sections close to edge have failed to develop appropriately. Section without graphite beneath can be seen as yellow strip. Sections with graphite beneath appear green.

etched by reactive ion etching (RIE) as described in [13]. These waveguides did not expose entirely to the edge as can be achieved with this method [12] although coverage is still improved and a FIB or laser cut may be used to reach these guides. They are currently being further processed to enable optical access of the waveguide end-faces and remove the graphitic layer with the aim of demonstrating in-plane coupling.

3. Non-optical characterisation – TEM of etched ridge

The sidewall and surface roughness of an optical waveguide are largely responsible for the attenuation in integrated optics [14]. In order to get a better indication of the roughness, sidewall angle and trenching effects of the fabricated ridge waveguides (previously estimated from scanning electron micrographs (SEMs)) we have used a transmission electron micrograph (TEM) of a ridge structure etched using the same procedure in single crystal diamond. Samples were prepared using a FIB based *ex-situ* liftout technique which involved an initial gold and platinum deposition over the waveguides to protect the surface from ion beam induced artefacts during this process [15].

Fig. 3A shows the right hand side of the etched ridge with the sidewall slope of 71°. The diamond and deposited gold and platinum layers are indicated. The dark line which runs across the middle of the diamond from the left is an artefact from the FIB milling of the TEM sample. Fig. 3B shows a higher magnification image of the inset labelled in Fig. 3A to highlight the surface roughness. In both images it can be seen that the diamond interface is extremely smooth (variation of a few nm) on both the top surface and the etched sidewall. This section is magnified from the inset defined in Fig. 3A in the Scanning TEM ("STEM") image in Fig. 4. Elemental maps corresponding to compositions of gold ("Au"), carbon ("C") and oxygen ("O") collected using an energy dispersive X-ray detector, are also shown in Fig. 4. The "C" signal outlines high carbon concentrations corresponding to diamond. An unexpected layer above the diamond at the base of the ridge is observed to be rich in oxygen. The outer surface of the as-fabricated waveguides are defined by the Au map, which corresponds to the sputter deposited layer in TEM sample preparation.

The formation of the oxygen-rich layer is attributed to the higher ion flux and off-angle ion bombardment at the sidewalls of the etched structures which is considered responsible for the trenching effect [16] and is seen in other diamond etching, for example [17]. For this etch process the diamond is not removed although this remaining modified region of high oxygen content may have some impact on optical guidance.

4. Nanostructures in diamond

The fabrication of slot-waveguides requires diamond structures of the order of 100 nm and narrower dimensions for the low index (air) slot where a large portion of the light is confined [9]. To fabricate these structures we have employed a new method using a FIB to perform the patterning [10]. The regions which are not to be etched are exposed with a dose of 10^{17} Ga^{+}/cm^{2} using a 30 kV, 11 pA beam from an FEI XP200 FIB system. This forms a surface on the diamond rich in gallium which gives high selectivity in an oxygen etch compared to the unexposed diamond. After exposure the sample is etched using the same RIE conditions for the ridge waveguides (O_2/CHF_3) to the

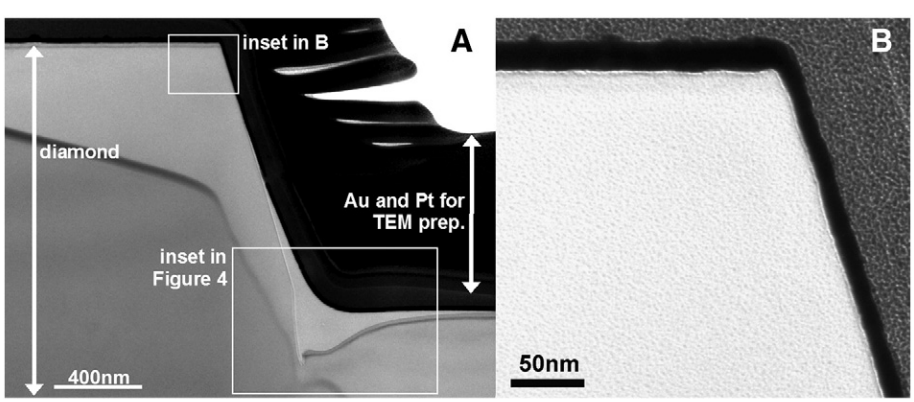

Fig. 3. Left – TEM of cross-section of right hand side of ridge etched into single crystal diamond by RIE. Right – TEM close up of top right corner of ridge.