Nanoscale Diamond Lenses for Atomic-Scale Sensing

Dominic E. Labanowski
Electrical Engineering, The Ohio State University, Columbus, OH

NNIN REU Site: Nanotech, University of California, Santa Barbara, CA
NNIN REU Principal Investigator: Prof. David Awschalom, Physics, University of California, Santa Barbara
NNIN REU Mentor: David Christle, Physics, University of California, Santa Barbara
Contact: labanowski.2@osu.edu, awsch@physics.ucsb.edu, christle@cnsi.ucsb.edu

Abstract:

Nitrogen-vacancy centers in diamond have demonstrated a number of useful room-temperature properties for applications in quantum information processing and magnetic sensing. The spin state of these defects can be optically initialized, manipulated using on-chip microwave fields, and optically read-out due to a spin-dependent contrast in photoluminescence. Because of diamond's high index of refraction, conventional optics collect only a fraction of the emitted photons. Solid immersion lenses (SIL) can drastically increase this collection efficiency, allowing for faster measurements and opportunities for new experiments such as "single shot" read-out. In this work, we discuss progress made in the fabrication of solid immersion lenses on the surface of diamond substrates using two techniques: focused ion beam milling and photoresist reflow. The shapes of the lenses made with both techniques were characterized and optimized, and their effect on increasing the collection efficiency of nitrogen-vacancy center photoluminescence was studied.

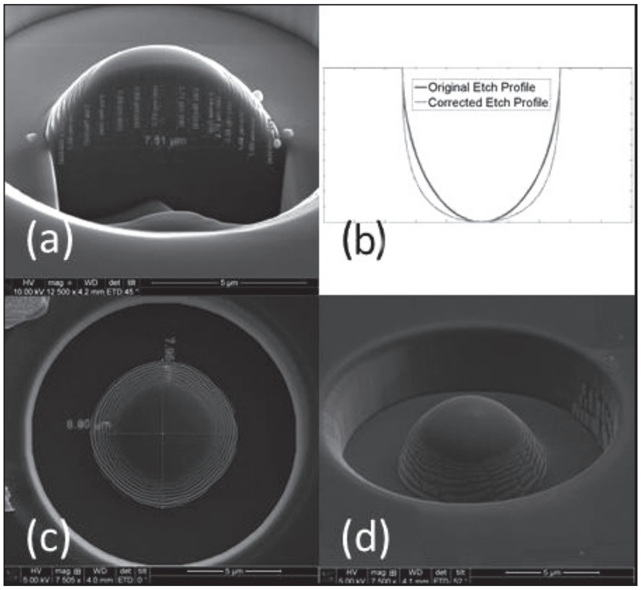

Figure 1: (a) SEM image of an uncorrected SIL cross-section. (b) Comparison of corrected and uncorrected SIL etch profiles. (c) and (d) SEM images of corrected SILs.

Experimental Procedure:

The initial stage of the project used a focused ion beam (FIB) system to mill hemispherical lenses directly on the surface of single-crystal diamond substrates using 30 kV accelerated Ga+ ions to sputter material from the surface. Initially, a perfectly hemispherical etch pattern was programmed into the FIB. The SIL fabricated using this method was then cross-sectioned and measured, shown in Figure 1(a). This cross-sectioning revealed non-linearities in the FIB etch, which lead to a non-hemispherical lens. SILs enhance the collection efficiency of nitrogen-vacancy (NV) center photoluminescence by centering a hemisphere on an NV center. This hemisphere allows for light leaving the NV center to exit the diamond normal to the surface at every point, lowering losses due to a mismatch in refractive indices between diamond and air (2.4 and 1, respectively).

Thus, fabricating perfectly hemispherical SILs is critical to observing this enhancement. In order to correct for these non-linearities, MATLAB® was used to apply a first-order correction to the etch pattern. A comparison of the initial FIB etch profile and the corrected etch profile can be seen in Figure 1(b). This new etch profile resulted in substantially more hemispherical etch profiles than previously obtained, shown in the SEM micrographs in Figures 1(c) and 1(d).

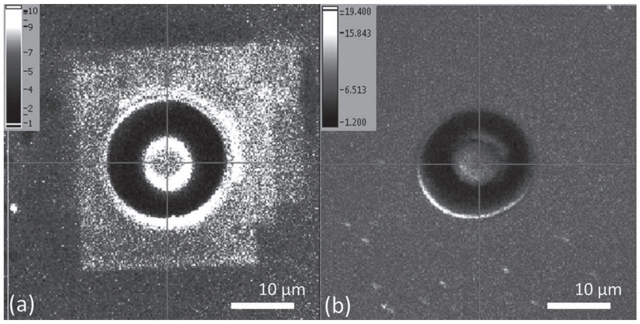

Figure 2: (a) Surface photoluminescence intensity before Ar/Cl_2 ICP etch. (b) Surface photoluminescence intensity after Ar/Cl_2 ICP etch.

To characterize the new SILs, they were placed into a home-built confocal fluorescence microscopy setup for spatial imaging of photoluminescence. The measured surface photoluminescence around the SILs, shown in Figure 2(a), was extremely high compared to the background elsewhere, making it impossible to image the NV centers within the SILs. It is likely that this background signal was due to Ga+ ion damage from the FIB etch, as is common in FIB etched structures. Chemically processing the sample using common solvents and boiling perchloric acid showed only a small reduction in the background surface photoluminescence.

Finally the surface of the samples was etched with an inductively coupled plasma (ICP) etcher using simultaneous Ar/Cl_2 gas flows to etch approximately 80 nm of diamond, removing the damaged layer entirely. This technique was effective in reducing surface photoluminescence around the SILs, as can be seen in Figure 2(b).

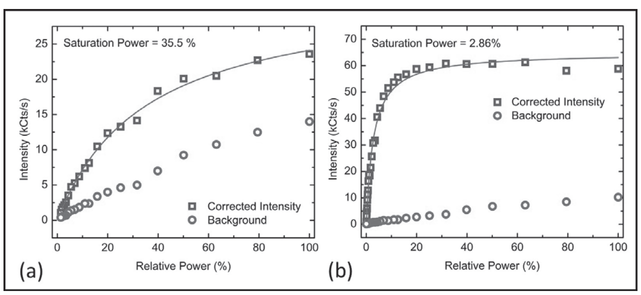

Figure 3: (a) NV center in bulk diamond. (b) NV center in SIL.

After the surface photoluminescence was reduced using the argon / chlorine etch, data were collected on the photoluminescence intensity of NV centers (both inside and outside the SILs), as a function of incident laser power. These plots can be found in Figure 3. The photoluminescence intensity increased by approximately a factor of three within the SILs, while background photoluminescence dropped by approximately a factor of two. This led to an increase in signal to noise ratio of approximately five for NV centers within SILs.

These increases, though still short of the theoretical enhancement of ~ 10x, allow for experiments to be done in substantially less time than was previously possible by reducing the amount of averaging necessary in what are essentially shot-noise limited measurements.

The final stage of the project focused on producing SILs using standard semiconductor processing techniques. While the FIB was effective in fabricating SILs, it was rather slow and expensive, producing one SIL for every hour of FIB time. If SIL production using photoresist reflow could be perfected, it would allow for the creation of thousands of SILs in just a few hours, at a very low cost per SIL.

In photoresist reflow etching, a thick layer (7 μm) of SPR220-7 photoresist was deposited on the diamond surface and patterned into pillars, shown in Figure 4(a). These pillars were then heated above the glass transition temperature of the photoresist in order to melt the pillars into more hemispherical shapes.

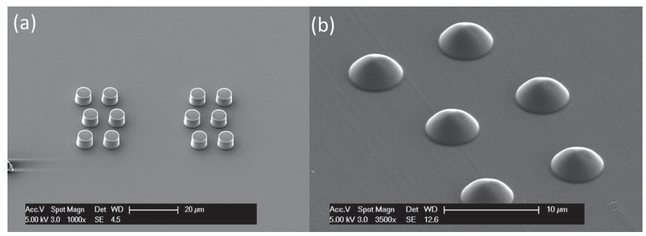

Figure 4: (a) Photoresist pillars before heating.
(b) Photoresist domes after heating.

After several rounds of trial and error, a temperature and heating time was found that led to relatively hemispherical resist patterns, shown in Figure 4(b). These photoresist domes were put into the ICP etcher and subjected to the same Ar/Cl_2 etch.

Unfortunately, low selectivity of this etch resulted in very shallow features (on the order of 200 nm) that deviated too much from the ideal hemispherical SIL profile desired for this research.

Conclusions:

We have demonstrated a method for the fabrication of SILs on the surface of diamond using a FIB. The SILs etched using this method have displayed the ability to significantly increase the photoluminescence from NV centers located within them, while reducing background.

In addition, a method was explored to produce SILs using semiconductor processing techniques, though no suitable SILs were fabricated using this method.

Acknowledgements:

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