Fabrication of high quality factor optical nanocavities in bulk single-crystal diamond

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Single-crystal diamond exhibits excellent optical properties which make it an attractive nanophotonics platform, due in part to its wide transparency window and vast inventory of luminescent defects. Integration of such color centers with monolithic diamond nanophotonic networks would ultimately enable scalable quantum information architectures and sensitive nanoscale magnetometry [1].

While nanophotonic devices are typically realized through scalable planar fabrication, whereby the device layer is a thin film optically isolated from a supporting substrate of a different material, *high quality* single-crystal diamond thin films do not exist. To address this, we recently demonstrated an 'angled-etching' nanofabrication method to realize suspended nanostructures in diamond [2]. Angled-etching employs anisotropic oxygen plasma etching at an oblique angle to the substrate surface, yielding suspended triangular cross-section nanobeams directly from bulk substrates.

Via our angled-etching methodology, single-crystal diamond waveguides perforated with a chirped lattice of air holes – which form a one-dimensional photonic crystal nanobeam cavity – were fabricated [3]. Devices designed to operate in the telecom band were confirmed to be high-Q, with Q-factors as high as 183,000 measured for the fundamental cavity resonance. For diamond nanobeam cavities fabricated for operation at visible wavelengths, the fundamental cavity modes exhibited Q-factors in the range of 5,000 to 8,000 (for wavelengths between 640 nm and 700 nm), a promising step forward in the pursuit of solid-state quantum repeaters based on diamond color centers[1].

In addition to nanobeam cavities, single-crystal diamond racetrack resonators were also realized by angled-etching [3]. To construct free-standing looped waveguide structures from a bulk substrate, vertical support structures, shown in Figure 3 (a-c), were employed. The vertical supports are achieved by positively tapering the waveguide width ~ 15 % of the nominal value over 20 μm long straight portions, such that a pedestal-like cross-section is achieved near the maximum support width. As such, the free-standing waveguide continues to efficiently route photons, while maintaining physical support through attachment to the bulk substrate.

A typical transmission spectrum, as shown in Figure 3 (d), reveals distinct transmission dips, with two modes supported by the structure evident. Lorentzian fits to transmission dips of each mode reveal Q-factors in excess of 10^5. From the measured Q-factors, the estimated diamond waveguide transmission loss is ~1.5 dB/cm. With these newly developed high-Q diamond optical nanocavities, bulk single-crystal diamond is now a viable nanophotonics platform servicing a wealth of applications, ranging from non-linear optics and chemical sensing, to quantum information processing and cavity optomechanics.

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[2] M.J. Burek *et al.*, Nano Letters **12**, 6084 (2012).
[3] M.J. Burek *et al.,* Nature Communications **5**, 5718 (2014).

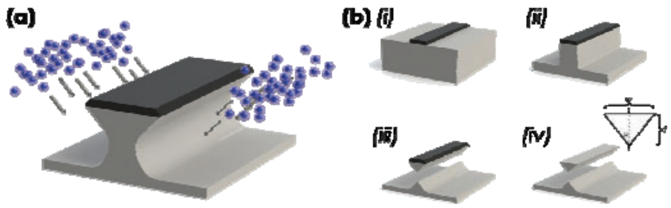

Figure 1. (a) Illustration of the angled-etching fabrication scheme used to realize free-standing structures in bulk single-crystal diamond. (b) Angled-etching fabrication steps: *(i)* define an etch mask on substrate via standard fabrication techniques, *(ii)* transfer etch mask pattern into the substrate by conventional top down plasma etching, *(iii)* employ angled-etching to realize suspended nanobeam structures, *(iv)* remove residual etch mask.

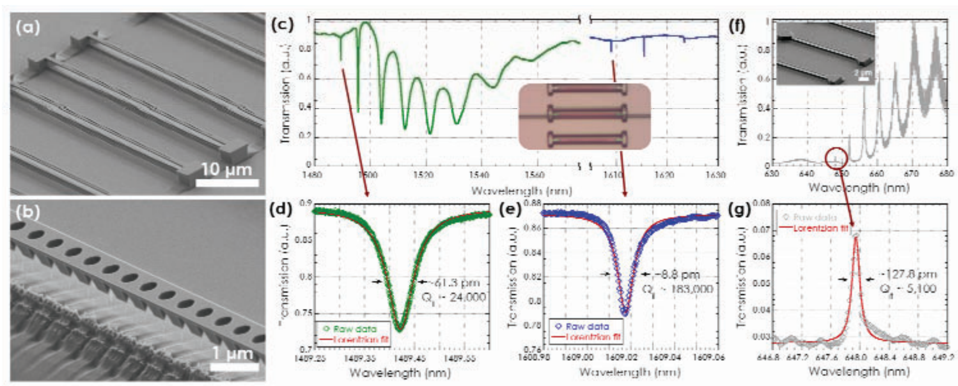

Figure 2. (a,b) SEM images of diamond nanobeam photonic crystal cavities. (c) Representative normalized broadband spectrum of a fabricated device collected by fiber taper measurement (inset indicates the tapered fiber coupling position). Corresponding high resolution spectra of the fundamental (d) TM-like and (e) TE-like cavity modes. (f) Representative normalized broadband visible transmission spectra collected via free space coupling, with inset of the fabricated device. Corresponding high resolution spectra of the fundamental (g) TE-like cavity mode.

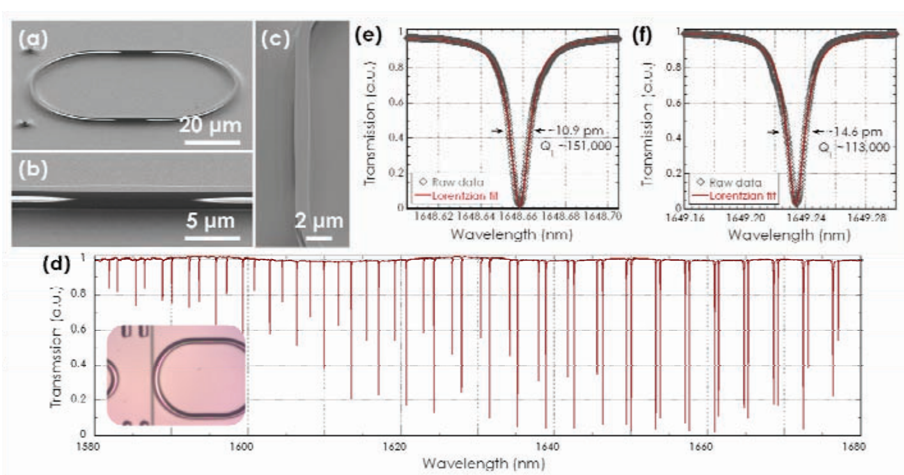

Figure 3. SEM images of (a) diamond racetrack resonator, with close-up (b) side and (c) top views of the vertical support. (d) Representative normalized broadband spectrum of a diamond racetrack resonator collected by tapered fiber measurement, with the fiber taper coupling position indicated by the inset. High-resolution spectra of near critically coupled (e) TE-like and (f) TM-like resonances with loaded Q-factors indicated.