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Novel fabrication of diamond nanophotonics coupled to single-photon detectors

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Freestanding diamond nanostructures are etched from a bulk diamond substrate and integrated with evanescently coupled superconducting nanowire single-photon detectors.

Diamond nanophotonics is a rapidly evolving platform in which non-classical light—emitted by defect centers in diamond—can be generated, manipulated, and detected in a single monolithic device (e.g., for quantum information processing applications).[1–3] Indeed, novel diamond fabrication techniques make it possible to engineer unique nanostructures in which diamond's extraordinary material properties (e.g., high refractive index, wide band gap, and large optical transmission window) can be exploited.[4,5] The relatively large Kerr non-linearity[6] of diamond also makes it an attractive platform for on-chip nonlinear optics at visible and IR wavelengths.[7] This nonlinearity could be used for frequency conversion of photons generated by color centers in diamond (i.e., from their typical visible wavelengths to telecom wavelengths).[8] In turn, this would enable transmission of quantum information and distribution of quantum entanglement[9,10] over long distances. Such integrated diamond–quantum photonics platforms would benefit from the use (and realization) of high-performance single-photon detectors that have broadband photon sensitivity and are integrated on the same diamond chip.

Superconducting nanowire single-photon detectors (SNSPDs) are a class of cutting-edge photon detectors that outperform other technologies in terms of detection efficiency, dark counts, timing jitter, and maximum count rates.[11–13] SNSPDs typically consist of narrow nanowires that are patterned into an ultra-thin (4–8nm) superconducting film.[14] The nanowires are biased close to the critical current of the superconductor material so that when an incident photon is absorbed by the wire, a small resistive hotspot forms and generates a voltage pulse, which is amplified and measured.[15]

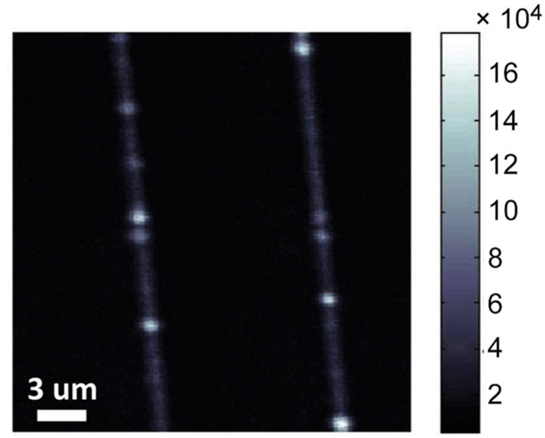

__Figure 1.__ Confocal scan of freestanding diamond waveguides, where bright spots indicate locations of implanted single nitrogen vacancy centers.

In our work,[16,17] we have developed a novel fabrication procedure with which we can etch freestanding diamond nanostructures directly from a bulk substrate. We use these freestanding diamond waveguides to guide the emission from diamond color centers—nitrogen[18] or silicon vacancies (NVs or SiVs), see Figure 1, that we implant within the waveguides—to evanescently coupled niobium titanium nitride SNSPDs. The evanescently coupled SNSPDs can thus be used to detect the color center fluorescence, while filtering out the pump laser that scatters into the waveguide.

A scanning electron microscope image of several freestanding diamond waveguides (with triangular cross sections) is shown in Figure 2(a). We etched these waveguides from single-crystal

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diamond with the use of our angled-etching fabrication method.[4] The waveguides are supported periodically by thin support structures underneath the waveguide that are created by slightly increasing the width of the waveguide at the support locations. This allows long segments of the waveguide to remain freestanding (while not perturbing the waveguide mode).[19] In addition, single meander SNSPDs—see Figure 2(b)—are located on both ends of the waveguide. The SNSPDs are then connected to titanium/gold contact pads for electrical readout.

Finite-difference time-domain simulations of the diamond waveguide SNSPD device are shown in Figure 3. The normalized field distribution of the optical mode in the diamond waveguide is shown in Figure 3(a), which illustrates the capacity for single-mode waveguide operation in the triangular cross section diamond waveguide. In addition, the absorption characteristics of the device—Figure 3(b)—indicate that more than 99% of the optical power has been absorbed by the SNSPD after a propagation distance of 15μm.

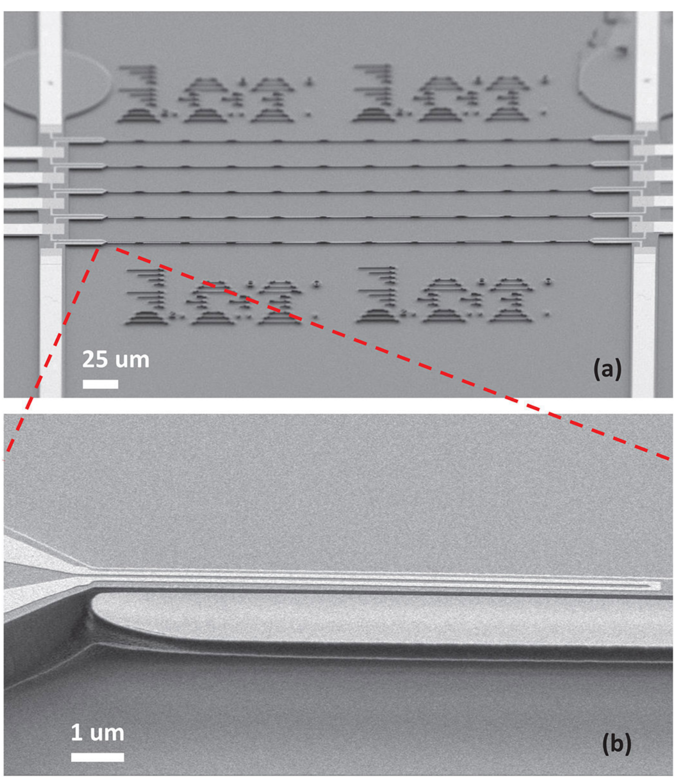

Figure 2. Scanning electron microscope images showing (a) several freestanding diamond waveguides (with triangular cross sections) that have two superconducting nanowire single-photon detectors (SNSPDs) at either end, and (b) an SNSPD patterned directly on top of the freestanding diamond waveguide.

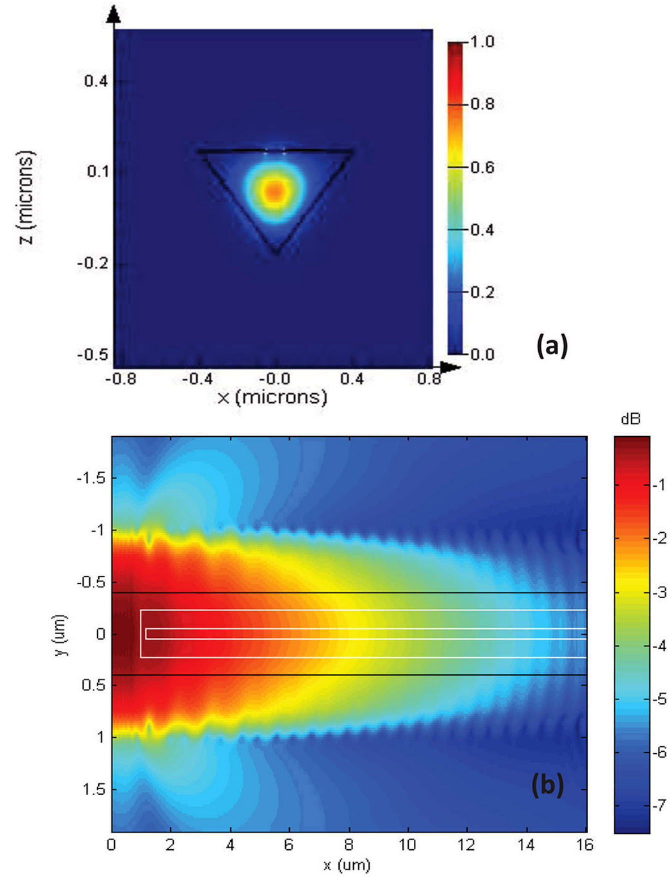

Figure 3. Finite-difference time-domain simulations of a diamond waveguide SNSPD. (a) Normalized field distribution of the optical mode in the waveguide. (b) Absorption characteristics of the device (propagation intensity shown on a logarithmic scale) along the propagation direction. White lines indicate the location of the 10.5nm-thick niobium titanium nitride superconducting nanowire.

The photon-counting performance of an SNSPD on one of the freestanding diamond waveguides (at 4.2K)—when illuminated with vertically incident 705nm photons—is depicted by the blue curve in Figure 4, and the red curve indicates the dark count response of the detector. The temperature (4.2K) and superconductor thickness (10.5nm) of the device limit the SNSPD from reaching a fully saturated photon count rate. However, we do observe a wide photon-counting operational range (i.e., the region where the device count rate begins to level off and approach an ideal saturated regime) that is still far from the detector's intrinsic dark counts.

In summary, we have developed a platform with which SNSPDs can be fabricated on freestanding waveguides that are

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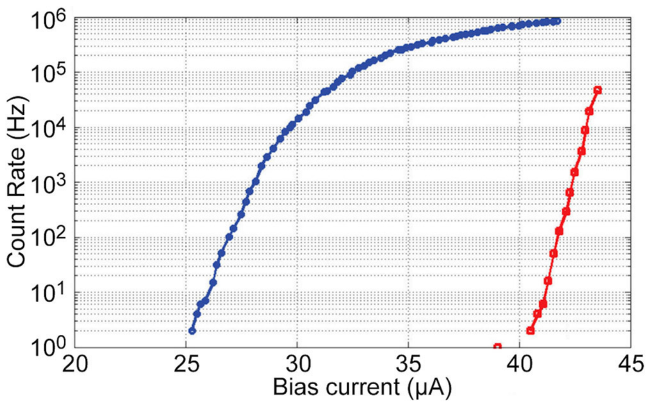

Figure 4. *Photon-counting performance of an SNSPD (at 4.2K) on a suspended diamond waveguide that is illuminated by 705nm photons. The intrinsic dark count rate and a representative count rate are shown by the red and blue curves, respectively.*

etched from single-crystal diamond (which can host quantum emitters with good spectral properties).[20] We have also characterized the photon-counting performance of our fabricated detectors. With our approach it is possible to achieve monolithic and scalable integration of diamond quantum optical circuits that are based on defect color centers. In the next stages of our work, we plan to improve the filtering of the pump beam (i.e., that is used to excite the color centers) so that the SNSPDs are no longer saturated by pump photons.

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