Efficient integration of high-purity diamond nanostructures into silicon nitride photonic circuits

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Abstract: A high purity diamond nanowire with implanted nitrogen-vacancy centers (NVs) is integrated into a low-loss silicon nitride photonic circuit. NV fluorescence is coupled into and collected from the waveguide system, paving the way for on-chip read out and manipulation of qubits.

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1. Introduction

The negatively charged nitrogen-vacancy center in diamond (NV) has a long lived spin state that can be initialized, manipulated, stored, and optically measured, giving it unique properties as an optically accessible solid state qubit [1]. Quantum network protocols based on these unique qualities have been proposed [2], and proof of principle network components have been demonstrated in diamond [1, 3]. However, the scalability of quantum networks based on diamond has thus far been limited due to challenges of large-scale diamond patterning.

On the other hand, silicon-based photonics is a mature field, making it possible to fabricate complex, large-scale integrated photonic circuits. However, the integration of optically addressable high-quality qubits has not yet been demonstrated. Here, we combine silicon-based photonic circuits and diamond spin-qubits in a hybrid system. We integrate ultrapure diamond nanostructures with implanted NVs into a large-scale photonic circuit leveraging the unique advantages of both systems and allowing for the creation of an efficient and powerful photonic quantum network.

2. Integration

Integrated photonic circuit components are fabricated in silicon nitride (SiN). Due to its large band gap of ~5eV, SiN supports low loss propagation of light in the visible spectrum. Single mode waveguides over the NV spectrum (600-800 nm) are fabricated with dimensions 400×400 nm. Fabrication steps are similar to those previously reported [4]. Light is coupled to the chip via inverse tapering of the waveguide to the chip edge and lensed fiber collection.

Short diamond single-mode waveguides (nanowires) are fabricated with dimensions of 0.2 μm×0.2 μm×6 μm. Simulations suggest that up to 80% of the emission from an NV is emitted into the diamond nanowire waveguide mode. Nanowires are placed over air gaps in the SiN waveguides (Fig. 1a). This crucial step isolates the SiN from the 532 excitation limiting unwanted waveguide fluorescence. It also gives a high index contrast for the integration of photonic crystal structures. The ends of the diamond nanowire and the SiN waveguides are slowly tapered (Fig. 1a) to promote an adiabatic-like transition between the diamond and SiN waveguide modes, limiting scattering loss. We estimate that with sufficiently long taper regions, up to 94% of the NV fluorescence emitted into the diamond waveguide mode will be transferred to the SiN waveguide. Diamond nanowires are integrated into SiN waveguides via a deterministic pick-and-place method that allows for precise sub-micron alignment of diamond to SiN.

3. Experiment and Results

NV centers in the diamond nanowire are excited via a confocal setup. On average 5 NVs are within the focal spot of the laser. Fluorescence is collected via the confocal setup into a single mode fiber, or through the waveguide into a lensed fiber. In both cases, the fluorescence is isolated from the laser by filters and sent to an APD or a spectrometer.
Counts

100
300
400
500
600

References

single photon sources. the first known instance of NV fluorescence coupled into a silicon based photonic circuit, paving the way for on-chip as that collected via the confocal setup when taking known losses into account. The results presented here constitute a beam splitter in the collection path, optics, and mode mismatch into the single mode collection fiber. In the waveguide collected through the waveguide as well as through the confocal setup. This confirms that NV fluorescence is coupled into the waveguide.

Fig. 1b shows scans of confocal excitation with confocal and waveguide collection. Fig. 2a shows close-up scans of confocal excitation at the center of the nanowire. The polarization of the excitation is optimized to minimize coupling of the excitation laser into the SiN waveguide to minimize background fluorescence in the collected signal. Fig. 2b compares spectra measured at the boxed regions in Fig. 2a collected confocally (blue) and through the waveguide (black). The zero phonon line at 638 nm and the features of the phonon side band are clearly seen in the fluorescence collected through the waveguide as well as through the confocal setup. This confirms that NV fluorescence is coupled into the waveguide.

Fig. 2. a) High resolution scan of the center of Fig. 1b with confocal and waveguide collection. b) Spectra of the marked spots in (a) normalized to integration time.

Under the assumption of circularly polarized signal due to fluorescence collected from many emission dipole directions, confocal collection is known to have a collection efficiency of approximately 25% with losses due to a polarizing beam splitter in the collection path, optics, and mode mismatch into the single mode collection fiber. In the waveguide system, known losses due to filtering and fiber-fiber coupling lead to a 50% collection efficiency. A comparison of the zero phonon line peak heights suggests that collection of NV signal through the waveguide is approximately the same as that collected via the confocal setup when taking known losses into account. The results presented here constitute the first known instance of NV fluorescence coupled into a silicon based photonic circuit, paving the way for on-chip single photon sources.

References