

Hybrid photonic integration of color centers in designer nanodiamond with SiN nanophotonic devices

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Abstract: We developed a new technique that enables deterministic assembly of diamond color centers in a SiN photonic circuit. Using this technique, we observed Purcell enhancement of SiV centers coupled to a silicon nitride ring resonator. © 2024 The Author(s)

1. Introduction

Diamond is a unique host material for a diverse range of color centers with remarkable optical and spin coherence [1]. This is largely due to its wide bandgap, exceptional chemical stability, and the feasibility of synthesizing single-crystal diamond with extremely low impurities at parts-per-billion level. Groundbreaking proof-of-concept experiments have been reported by employing diamond color centers as single-photon emitters or optically accessible spin qubits [2], including single-photon generation, entanglement distribution and swapping, quantum teleportation, and memory-enhanced quantum communication. To improve the performance and scalability of these applications requires the integration of diamond color centers with scalable photonic circuits [3]. However, despite significant advancements in diamond fabrication in the past decade, creating large-scale photonic circuits in diamond remains a significant challenge. Additionally, the stochastic nature of color center creation makes it difficult to achieve scalable and deterministic integration of color centers with photonic circuits.

Hybrid integration, the process of integrating quantum emitters with photonic circuits in a heterogeneous material, provides a viable solution to both aforementioned challenges. Hybrid integration allows us to take the best of both worlds, the high-quality quantum emitters and spins based on color centers in diamond, and the wafer-scale integrated photonic circuits in fabrication-friendly materials such as Silicon Nitride (SiN). In addition, one can use pre-selected quantum emitters for photonic integration, making hybrid integration a scalable way to assemble complex quantum photonic circuits. Two different approaches have been developed for hybrid integration of diamond color centers with heterogeneous photonic circuits. The first one relies on the pick- and-place technique [4], where diamond photonic devices containing color centers are picked up from a diamond substrate and placed onto sockets defined on a heterogeneous photonic circuit. This approach allows for the maximum possible coupling between the color center and the diamond photonic device such as a waveguide or a cavity. However, it suffers from a relatively large insertion loss (typically a few dB [4]) at the interface between the diamond waveguide and the photonic circuit, due to a combination of placement errors and photon scattering. The second approach relies on evanescent coupling of diamond color centers with photonic devices defined completely in the heterogeneous material [5]. This can be achieved by fabrication of photonic devices in a high-refractive-index material deposited on single-crystal diamond, or by placing nanodiamonds on top of a photonic device defined in a heterogeneous material. While this approach avoids insertion loss at the material interface, it suffers from weak evanescent coupling between the quantum emitter and the photonic device.

In this talk, I will report a new hybrid integration approach that has the potential to achieve the maximum possible light-matter interaction strength while maintaining low insertion loss at the material interface [6]. Relying on our pick-and-place technique, any preselected nanodiamond can be efficiently transferred to the SiN target substrate. The transferred nanodiamond can be embedded in between the SiN layer by SiN post growth, that allows the SiV center to meet the maximal optical field when a structure is fabricated aligning with the nanodiamond. Using our method, we demonstrate the coupling to SiN nanobeam waveguide and ring cavity.

2. Coupling between SiV centers with SiN devices

Our integration method begins with fabrication of diamond nanopillars hosting SiVs followed by partial undercut (Fig 1a). The pillar with thin neck enables deterministic break-off from the base diamond substrate and subsequent transfer and assembly on a SiN substrate with a nano-probe integrated in SEM (Fig 1b). We call these nanopillar as designer nanodiamond. A second growth of SiN following the transfer process covers the nanodiamond right at the center of the whole SiN layer. Following by standard E-beam lithography, any device can

be fabricated atop the nanodiamond. Since the nanodiamond is embedded inside the SiN structure, the coupling between SiV and optical mode is non-evanescent, that allows the maximal possible light-emitter coupling strength.

We first demonstrate the coupling of SiV center to a SiN nanobeam waveguide. The integrated device is shown in Figure 1c, with a red arrow pointing to the location of the embedded nanodiamond. The coupling is evidenced by the collection of SiV PL spectra from two output ports of this 50:50 power splitter, both measured PL spectra are identical with the PL spectra collected directly from the top of the nanodiamond.

Based on the deterministic nature of the integration method, we further show Purcell enhancement by integrating the SiV center to a SiN ring cavity (Fig 1h). As we tune the cavity resonances across each zero-phonon line of the SiV center, the emission intensity is enhanced by 2 times when it is on resonance with the cavity. In addition, a 6.5% lifetime reduction suggests a lower limit for the Purcell factor $F = 2$.

To further validate our hybrid integration method, we keep track of the optical coherence (e.g. photoluminescence excitation (Fig 1d-e), optical lifetime, and spectral diffusion (Fig 1f-g).) of the SiV center in the SiN waveguide at each integration step. We have observed no deleterious impact on the SiV optical properties after the integration in all four SiN devices.

In summary, our new method enables deterministic integration of color centers to generic thin film material. Which allows the maximal possible coupling between pre-selected nanodiamond and desired photonic device. We demonstrate the coupling to SiN waveguide and ring cavity. Improved fabrication technique and the use of smaller nanodiamond can lead to a larger Purcell enhancement. Our method paves the way to scalable manufacturing of quantum photonic circuits integrated with high-quality quantum emitters and spins.

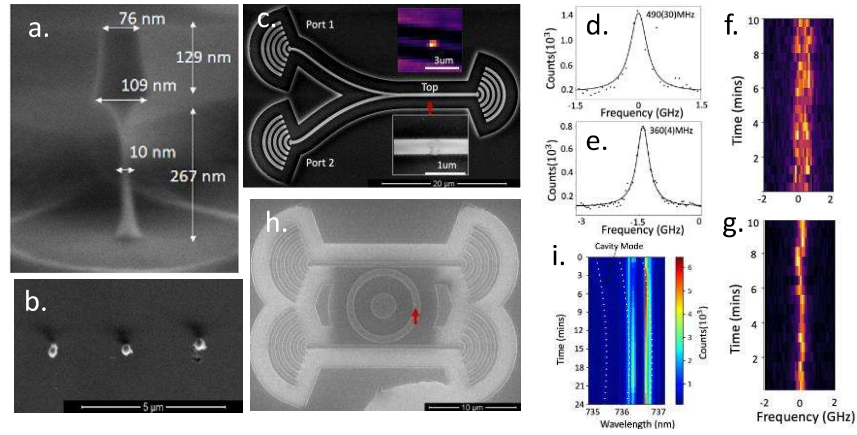


Fig. 1. (a) Side viewed SEM image of the designer nanodiamond. (b) Deterministic assembly of designer nanodiamonds into a line. (c) SEM image of a SiN photonic circuit (50:50 power splitter) integrated with a single designer nanodiamond embedded inside the waveguide. The bottom inset is an SEM image of a zoom-in image of the area centered around the designer nanodiamond. The top insert shows the scanning confocal photoluminescence image of the area centered around the designer nanodiamond. (d-e) Photoluminescence excitation spectra of the same optical transition from the same SiV center before (d) and after (e) the integration of the designer nanodiamond with the SiN photonics in (c). (f-g) Photoluminescence excitation spectra of the same optical transition shown in (d) and (e) recorded for 10 minutes before (f) and after (g) the integration of the designer nanodiamond with the SiN photonics. (h) SEM image of the SiN ring cavity integrated with a single designer nanodiamond. The red arrow indicates the position of the integrated designer nanodiamond. (i) Photoluminescence spectra of the SiV center as a function of time. The white dashed lines indicate the resonance of each cavity mode as a function of time.

3. References

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