Towards Efficient Spin-Photon Interfaces for Scalable Quantum Networks on Photonics Integrated Circuits

Tim Schroder, Luozhou Li, Edward H. Chen, Michael Walsh, Igal Bayn, Faraz Najafi, Sara Mouradian, Matthew E. Trusheim, Ming Lu, Mircea Cotlet, Matthew L. Markham, Faraz Najafi, Karl Berggren, Daniel J. Twitchen & Dirk Englund

1 Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
2 Center for Functional Nanomaterials, Brookhaven National Laboratory, Upton, NY, 11973, USA
3 Element Six, 3901 Burton Drive, Santa Clara, CA 95054, USA
*corresponding author: englund@mit.edu

Abstract. We discuss recent progress towards building on-chip quantum networks of multiple spin qubits in nitrogen vacancy (NV) centers in diamond. An essential component for such networks is an efficient light-matter interface to entangle photons and stationary qubits. Here, we describe NV-nanocavity systems in the strong Purcell regime with optical quality factors approaching 10,000 and electron spin coherence times approaching the millisecond regime; patterned NV-cavity implantation; and techniques for high-yield integration multiple functional NV-cavity systems and single photon detectors on-chip.

A central goal of quantum information science is the production of large entangled states with individually controllable quantum memories. Quantum networks, consisting of optically connected long-lived stationary quantum memories, are an attractive path towards this goal. Among solid-state systems, the nitrogen-vacancy center in diamond has emerged as an excellent optically addressable memory with second-scale electron spin coherence times [1]. Recently, quantum entanglement and teleportation have been shown between two nitrogen-vacancy memories [2] despite very lossy optical channels connecting them. However, scaling to larger networks will likely require more efficient spin-photon interfaces based on optical resonators and efficient nanophotonic collection strategies. Here, we discuss progress towards the development of on-chip networks of multiple NV quantum memories entangled via photons in photonic integrated circuits (PICs) and on-chip photodetection.

Figure 1 shows photonic crystal nanobeam cavities produced in high-quality single crystal diamond grown by chemical vapor deposition (CVD) by Element6. The diamond was thinned using mechanical polishing and oxygen reactive ion etching (RIE); the cavities were produced using a silicon hard mask that was mechanically transferred onto the diamond membrane [3]. Such silicon hard masks enable excellent selectivity for oxygen RIE, which makes them also useful for producing triangular waveguide networks in diamond [4]. In cavities as in Figure 1, which have mode volumes on the scale of the wavelength cubed and measured Q values as high as 10,000, we measured the NV’s spontaneous emission rate to be enhanced by more than 50 times [5], and, using integrated microwave wires to perform optically detected magnetic resonance, electron spin-coherence times exceeding 200 µs.

To improve the probability that NVs are overlapped with the cavity field maximum, we recently developed an implantation technique that uses the same silicon hard mask that is used for the photonic crystal etching. Using a combination of reactive on etching and aluminum oxide deposition, we are able to create implantation masks with a thickness of 270 nm and with through-holes with a dimension down to 1 nm. Proof-of-concept experiments with $^{15}$N implantation at energies of 6 and 20 keV resulted in NVs with a FWHM down to 26±2.4 nm – limited, at this point, by straggle rather than the mask feature size [6]. When this targeted implantation approach is applied NV production in the cavity, we observe a strong improvement in the yield of highly coupled...
NV-cavity systems, with $\sim 1$ NVs/cavity area [7].

However, even the targeted implantation is not fully deterministic since the number distribution of NVs in the cavity follows a Poisson distribution. To address this problem, we therefore developed a hybrid process in which NV quantum memories and the PICs are produced separately, and functional components are finally assembled. We have designed an adiabatic tapering between the SiN and diamond waveguides to enable an efficient photon transfer between them. The NV centers in these diamond nanowires exhibit relatively narrow linewidths of several hundred MHz at low temperature, evaluated by resonant excitation. We estimate that $> 10^6$ photons/second are coupled into the SiN waveguide. This approach facilitates the assembly of multiple quantum memories into a photonic integrated circuit with high yield [8].

On-chip detection can also help improve the optical collection efficiency, since it avoids the $\sim 3$dB photon loss that we normally incur when coupling into a silica fiber from the photonic circuit. To this end, we recently developed a fabrication to integrate superconducting nanowire single photon detectors on photonic waveguides [9].

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**REFERENCES**