13 - Diamond Integrated Quantum Photonics

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Status

Over the past decade, color centers in diamond have been explored with the goal of utilizing their optically accessible spin for the implementation of quantum photonics and quantum networks [1,2]. These networks could be constructed from a series of nodes comprising color centers embedded in nanophotonic cavities, connected to each other via telecommunications fibers. The nodes act as quantum repeaters and processors, and enable novel, optically mediated entanglement topologies over distances for which photon loss would make direct transmission of entanglement impossible. Realization of such a network would enable technologies such as long distance QKD, distributed quantum computing, and enhanced long-distance quantum sensing [2].

Several breakthroughs towards this goal have already been achieved utilizing two primary color centers, the negatively charged nitrogen-vacancy (NV) center (see Fig. 1a) and the negatively charged silicon-vacancy (SiV) center [1] (see Fig. 1b). The NV center has been used to demonstrate loophole-free, photon-mediated entanglement between distant spins [3], as well as deterministic delivery of entanglement at a rate which exceeds the decoherence rate of the entangled state [4]. In parallel, the coherence properties of the NV spin have been improved to over a second [5]. Neighboring nuclear spins have also been harnessed through the NV spin as long-lived ancilla qubits and memories culminating in the realization of a 10-qubit quantum register and entanglement of 7 qubits [6].

More recently, the SiV center has attracted interest due to its superior optical properties [1]. In particular, the SiV maintains its charge and spectral stability when integrated into nanophotonic cavities. This property has enabled the realization of an integrated, SiV-controlled single photon switch [7], coherent interaction of two SiV spins through the optical mode of a photonic cavity [8], and memory-enhanced photonic Bell-state measurements [9] (see Figs. 2a and 2b). The cooperativity of the spin-photon interface enabled by the nanophotonic cavities now reaches above 100, thus indicating reliable coupling between itinerant photons and the SiV spin memory. Tapered waveguides allow the extraction into an optical fiber of more than 90% of SiV photons emitted into waveguides (see Figs. 2a and 2b). Integration of nanophotonic devices comprising SiV color centers with mechanical devices [10] and nonlinear optics platforms has also been demonstrated [11].

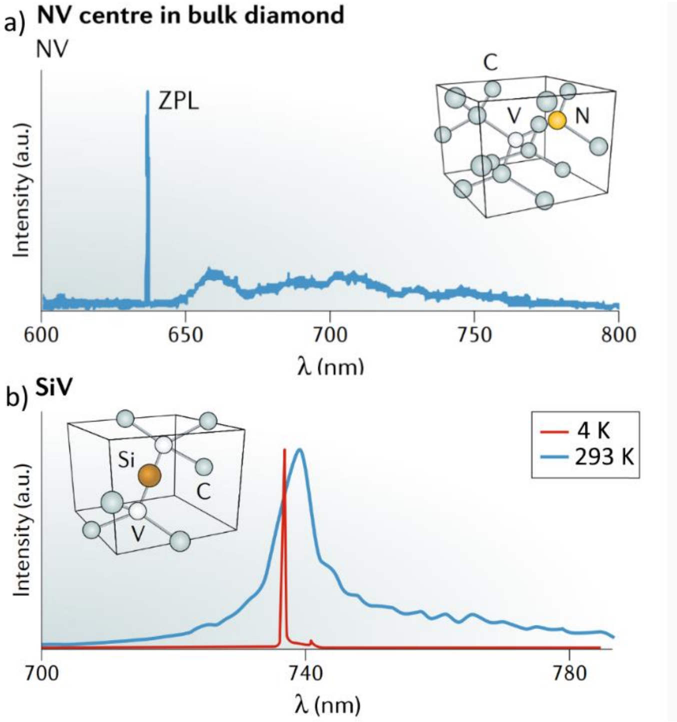

Figure 1. Fluorescence spectra of the two most prominent diamond color centers. **a)** The negatively charged nitrogen-vacancy (NV) center displays a sharp zero-phonon line (ZPL) amounting to 4% of the total emission at 4K, with the rest corresponding to the broad phonon sideband. **b)** The negatively charged silicon-vacancy (SiV) center has 70 to 80% of its emission into the ZPL. Among the dozens of known diamond color centers these two are the most studied, as they offer long-lived, optically-accessible spin qubits. The structures of the color centers (insets) explain the differences between their properties. The inversion symmetry of the SiV reduces its sensitivity to stray electric fields but also introduces increased sensitivity to thermal phonons. Other group IV color centers such as the germanium- (GeV) and tin- (SnV) vacancy centers share the structure of the SiV, making them promising candidates for further study [10]. a) and b) are reproduced with permission from [1].

Current and Future Challenges

Both the NV and SiV platforms have demonstrated the individual components required for the creation of quantum networks with quantum repeaters (see Fig. 2c), and are now pursuing integration of the required technologies and enhancement of optically mediated entanglement rates.

The highest rate of photon-mediated entanglement between two NV center spins is currently 39 Hz [2,4]. This rate is limited by the 4% probability that the NV emits photons into its zero phonon line (ZPL) (see Fig. 1a) and by a limited collection efficiency. This can be addressed by embedding NVs into optical cavities, which in the case of fiber cavities has enabled a 10-fold Purcell enhancement [12]. Further integration requires the use of nanophotonic cavities fabricated directly in diamond, which is hampered by spectral instability of the NV near surfaces [13].

Such nanophotonic cavities, as successfully used for SiV experiments (see Fig. 2b), remain difficult to fabricate due to the lack of techniques for heteroepitaxial growth of pure, single-crystal diamond. Instead, several techniques have been used to undercut devices in bulk diamond [13]. Among these, crystallographic and angled etching are the most promising, but can produce only specific device topologies.

Furthermore, to enable large spin-photon coupling, photonic cavities rely on small mode-volumes. Reproducibility remains a challenge for such cavities due to the limited precision with which color centers can be localized through implantation and due to fabrication-induced damage. Crystal damage also causes spectral instability and inhomogeneity between centers [13]. This is a limiting factor in scaling up to larger networks, as photons most easily couple emitters with the same transition energies.

The design of larger networks will also require color centers to be integrated into or coupled to other photonic platforms for photon routing, manipulation, and conversion to telecom wavelengths [11,13]. Further integration with other quantum computing platforms, such as superconducting qubits or trapped ions, will be beneficial to hybrid approaches to quantum information processing.

Finally, much progress could be made through the search for novel color centers combining superior spin and optical properties [14]. These properties can include high photon yield into the ZPL with near unity quantum efficiency, long spin coherence times with optical addressability at elevated temperatures, or low sensitivity to strain, charge and magnetic noise.

Advances in Science and Technology to Meet Challenges

Ongoing theoretical and experimental research efforts have led to several proposed solutions for the challenges facing diamond color center-based quantum networks.

Of primary interest is improving the understanding and control of the elements that impact the inherent properties of color centers. This is especially important for the NV center, but would also contribute to the development of new surface treatments, implantation techniques, annealing parameters, growth conditions, and novel strategies such as shallow implantation followed by overgrowth that could improve the properties of all forms of color centers [13].

Narrowing the range of novel emitters that need to be explored experimentally requires a systematic understanding of the desired properties of emitters and further improvement of computational methods for evaluating candidates [15]. The related efforts into reducing the cost and improving cooling power of cryogenic technologies are also important for increasing academic and industrial access to new color center technologies.

The improvement of cavities for spin-photon interfaces and their integration with new technologies requires progress in fabrication techniques. The most developed fabrication strategies rely on undercut photonic devices that can still be optimized further, while novel techniques involving the use of suspended diamond films that could enable more straightforward device fabrication require more investigation. Future diamond platforms should also continue to integrate microwave, acoustic, and electromechanical functionalities as control mechanisms for color centers [10,13]. Improving access to ultrapure diamond substrates and facilities for overgrowth of existing substrates remains an ongoing and important effort.

The parameter space of existing techniques for nanophotonic device design also remains underexplored. Larger mode volume cavities could be coupled to NV centers, overcoupled or ultrasmall mode volume cavities could enable higher cooperativity or more efficient spin-photon gates, and inverse design techniques could be used to enable more sophisticated device properties [13,16].

Finally, permanent packaging of diamond photonic devices that allow simultaneous addressing of multiple color centers will be essential to large scale integration. This could be accomplished by permanent splicing of fibers onto existing devices, pick-and-place integration with other platforms [11], or flip-chip technology [13].

Concluding Remarks

Driven by progress in nanofabrication, theoretical understanding, and experimental sophistication, diamond color centers coupled to nanophotonic devices have emerged as a leading photonics and quantum communication platform. Technology surrounding the NV center has progressed furthest, resulting in demonstrations of long distance entanglement. The entanglement rates could be boosted to technologically relevant levels with the development of techniques for integration of the color center with cavities. The SiV center has been successfully integrated with nanofabricated cavities, has been used to demonstrate enhancement of quantum communication rates, and is progressing rapidly towards similar demonstrations of long distance entanglement. Meanwhile, ongoing research into other color centers could lead to the discovery of emitters which can combine the best properties of

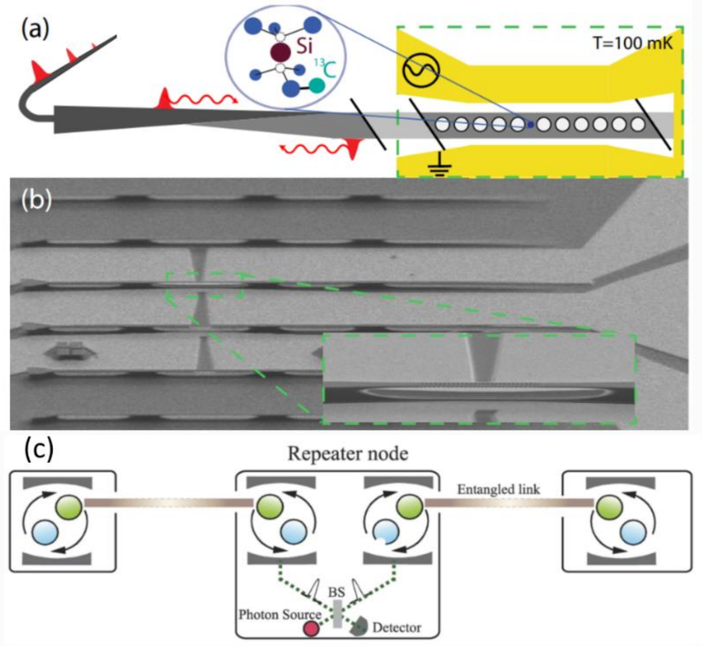

Figure 2: Example structure of a quantum network node. **a)** Schematic of the experimental setup used in Ref. [5]. SiV centers are embedded in a nanophotonic cavity, surrounded by gold coplanar waveguides for spin control. Photons produced by the color centers are collected through the tapered fiber interface at the end of the device. **b)** Scanning electron microscopy (SEM) image of the device shown in panel a) Inset shows the nanophotonic crystal cavity. **c)** Schematic representation of a general quantum repeater node. A pair of quantum emitters inside cavities are placed at each node. The nature of the emitters and cavities varies depending on the platform used. After successfully heralding entanglement with adjacent nodes, Bell-state measurements are performed between the memories in the two cavities to teleport entanglement to the distant nodes. a) and b) are reprinted with permission from C.T. Nguyen, D.D. Sukachev, M.K. Bhaskar, B. Machielse, D.S. Levonian, E.N. Knall, P. Stroganov, R. Riedinger, H. Park, M. Lončar, and M.D. Lukin, "Quantum network nodes based on diamond qubits with an efficient nanophotonic interface", *Phys. Rev. Lett.*, vol. 123, pages 183602, 2019. https://doi.org/10.1103/PhysRevLett.123.183602. Copyright 2019 by the American Physical Society. c) is reprinted from K. Nemoto, M. Trupke, S. J. Devitt, B. Scharfenberger, K. Buczak, J. Schmiedmayer, and W. J. Munro, Photonic Quantum Networks formed from NV− centers, *Scientific Reports*, vol. 6, pag. 26284 2016, under a Creative Commons Attribution 4.0 International License http://creativecommons.org/licenses/by/4.0/

existing platforms. The challenges for these platforms lie primarily on the road to large scale integration, as the individual components required for near term application for quantum networking technologies have been demonstrated.

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