

Diamonds for scalable quantum information systems

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Optical control of individual electron and nuclear spins in a diamond host can be used to construct scalable quantum computers, repeaters, and quantum memories, with much achievable at room temperature.

Enormous potential lies in the weird quantum world for a new generation of information systems that address important and unsolved problems in secure communications, high-performance computing, data storage, and simulation. Surprisingly, single crystal diamond (SCD), long known for its allure as a gemstone, has just the right properties for fabricating critical components that will serve as building blocks of this new quantum technology.

A key requirement for useful quantum information devices is the ability to create shared quantum entanglement among large numbers of quantum bits (qubits) independent of their physical locations. This is best done using optical photons, especially for long-distance secure quantum communication applications. However, because photons do not make good quantum memories, a system with long-lived qubits, such as spins and a high-fidelity quantum interface to photons would be highly desirable. Although trapped ions are potentially capable of fulfilling this need, there is no substitute for solid-state implementation for ease of scaling and integration.

Our approach is to use nitrogen-vacancy (NV) color centers in diamond. These consist of a nitrogen atom paired with a vacancy in the diamond lattice. They provide strong optical transitions that scatter photons efficiently enough to allow individual NVs to be easily visualized with a confocal microscope.¹ Unlike most optical emitters, the NV has a ground state with three electron spin sublevels. Proximal nuclear spins provide additional degrees of freedom,² resulting in numerous choices for qubit encoding. Spin coherence times for such qubits are unusually long, even at room temperature, rivaled only by ion qubits trapped in high vacuum. It is estimated that up to a million single qubit operations can be performed within the NV spin coherence lifetime.

Through a fortunate interaction with the singlet excited states, the NV can be spin-polarized to a high degree by illumination with broadband light, such as an LED flashlight, even at room temperature. Equally fortuitous is the fact that one of the electron spin sublevels undergoes an optical cycling transition that is pure enough, at liquid helium temperatures, to allow single-shot spin readout.¹ Even at room temperature, this cycling transition is adequate for such a readout if half of the emitted photons can be detected. Encouragingly, our recent theoretical estimates³ and pilot experiments⁴ with optical plasmon nanowires suggest this might soon be possible.

At room temperature, we have demonstrated each of the key elements needed to build few-qubit quantum processors with enough functionality for quantum repeater nodes.⁵ Specifically, we showed that arbitrary electron spin coherences can be transferred to a nuclear spin where they can be stored for up to a fraction of second and recovered with high fidelity. Furthermore, the stored nuclear spin is sufficiently robust for optical re-initialization cycles of the electron spin, as required for a quantum repeater memory. We also observed multi-qubit interactions between the NV electron spin and nearby nuclear⁶ and electron⁷ spins up to nanometers away.

We are currently in the process of creating long-distance entanglement between pairs of NVs using optical measurements. So far, we have demonstrated narrowband, electrically tunable,⁸ optical transitions stable enough to allow spontaneous photons, emitted minutes apart, to produce optical interference fringes.⁹ We have also demonstrated optical Raman spin-flip transitions on one branch of the excited state while simultaneously maintaining an optical cycling transition on the other.¹⁰

In summary, we can report surprising progress in realizing scalable quantum information systems with NV color centers in diamond (see Table 1). In the future, we plan to develop large-scale photonic circuits that optically couple numerous NV qubits to construct advanced quantum processors, and high-performance spintronic devices.¹¹

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Table 1. Status of NV diamond relative to DiVincenzo criteria.

| | Criteria | Low temp | Room temp |
|----------|---|------------------|------------------|
| 1 | Well-defined qubits | ✓ | ✓ |
| 2 | Initialization to a pure state | ✓ | ✓ |
| 3 | Universal set of quantum gates | ✓ | ✓ |
| 4 | Qubit-specific measurement | ✓ | Progressing well |
| 5 | Long coherence times | ✓ | ✓ |
| 6 | Interconvert stationary and flying qubits | Progressing well | Maybe |
| 7 | Transmit flying qubits to distant locations | Progressing well | Progressing well |

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