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Viewpoint

Diamond Spins Shining Bright

Guido Burkard
Department of Physics, University of Konstanz, D-78457 Konstanz, Germany

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The spin on a silicon defect in diamond can be prepared in a coherent quantum state, a promising sign that it could encode information in a quantum internet.

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A Viewpoint on:
All-Optical Initialization, Readout, and Coherent Preparation of Single Silicon-Vacancy Spins in Diamond
Lachlan J. Rogers, Kay D. Jahnke, Mathias H. Metsch, Alp Sipahigil, Jan M. Binder, Tokuyuki Teraji, Hitoshi Sumiya, Junichi Isoya, Mikhail D. Lukin, Philip Hemmer, and Fedor Jelezko
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All-Optical Formation of Coherent Dark States of Silicon-Vacancy Spins in Diamond
Benjamin Pingault, Jonas N. Becker, Carsten H. H. Schulte, Carsten Arend, Christian Hepp, Tillmann Godde, Alexander I. Tartakovskii, Matthew Markham, Christoph Becher, and Mete Atatüre
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The quantum internet of the future could take many forms, but its core components will be quantum bits (qubits) that can store information and qubits that can carry information [1, 2]. Atom-sized defects in diamond called silicon vacancy centers are promising candidates as the storage component: they possess a single spin whose quantum state (such as a superposition between "up" and "down") could encode information. This stored information can also be precisely imprinted on the light the defects emit when excited optically. Independent research groups led by Fedor Jelezko at Ulm University in Germany [3] and by Mete Atatüre at Cambridge University in the UK [4] have now measured the coherence time T_2^* of the spin on a negatively charged silicon vacancy (SiV) center, a key quantity determining how long the coherent superposition of up and down states can be maintained. Although the measured coherence time is only on the order of tens of nanoseconds (ns), a number of strategies exist to increase it to the point that SiV centers could be viable quantum internet components.

For all candidate qubits, a tradeoff exists between better and faster control and a long coherence time. The spin states of ions floating in vacuum have a coherence time T_2^* approaching 1 minute [5] (see 24 November 2014 Viewpoint), but rotating them is a slow process. In comparison, electron spin states on semiconductor quantum dots can be quickly rotated electrically or optically, but the best coherence times seen so far are typically less than microseconds [6]. Spin qubits associated with defects in diamond lie somewhere in the middle of these two extremes: Because diamond has a large band gap, there aren't many states that a spin qubit could decay into, and, on some defects, the spin's state can be quickly rotated with light. Most research so far has focused on spin states associated with nitrogen vacancy (NV) centers, in which a nitrogen atom substitutes for a carbon atom that sits next to a vacant atom site. The spin states of NV centers have coherence times of roughly microseconds and can be controlled even at room temperature [7].

In the SiV center, Si substitutes for one of the missing carbon atoms. Like the NV center, the negatively charged SiV center carries an electronic spin in its ground state. But despite similarities between the two defects, there are important differences: The N atom and its adjacent vacancy break the inversion symmetry of the diamond crystal. In contrast, the Si atom in the SiV center sits halfway between two vacant carbon sites (Fig. 1). Because this configuration is symmetric under inversion, the SiV center is relatively insensitive to stray electric field fluctuations and, as a result, photons emitted from the SiV center have a narrow linewidth around a bright peak [8]. This feature is desirable for quantum communications applications, such as preparing indistinguishable photons that can be entangled. Finally, compared to NV centers, SiV centers are much less likely to lose energy by exciting vibrations (phonons) in the surrounding diamond lattice.

Despite its many attributes for quantum communication, the SiV center has a handicap: its ground state consists of two degenerate states with different orbital configurations. The defect is therefore unstable towards

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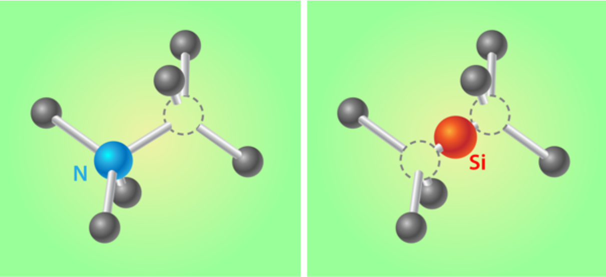

FIG. 1: Two defects in diamond. The nitrogen vacancy (NV) center (left) and the silicon vacancy (SiV) center (right) both possess a single spin that can store information and be manipulated optically. The SiV center, however, doesn't break the inversion symmetry of the diamond lattice, a feature that leads to the defect emitting light that is more sharply peaked at a particular frequency than that emitted by the NV center. (APS/Alan Stonebraker)

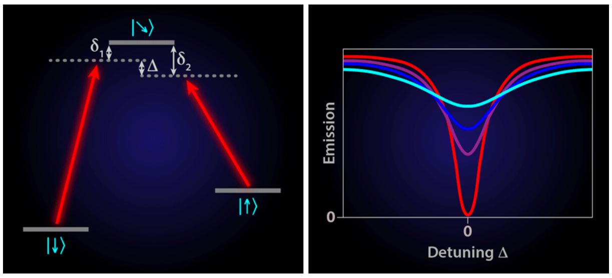

FIG. 2: Coherent population trapping (CPT). (Left) Two lasers excite the energy levels associated with opposite spin states to a common excited state. When the detuning Δ from the two-photon resonance is small, the levels will relax into a dark state, from which excitation and re-emission of light is suppressed. (Right) In the absence of decoherence, emission approaches zero when the detuning is small (red curve). When the decoherence rate increases, the emission dip becomes shallower and broader (purple, blue, and cyan curves). (APS/Alan Stonebraker)

a lattice distortion, known as the static Jahn-Teller (JT) effect. Moreover, interactions between electrons on the SiV center and phonons in the lattice cause the SiV center to switch rapidly between its two ground-state orbitals, a phenomenon known as the dynamic JT effect. Because the spin state is weakly coupled to the orbital state, the JT effect is expected to limit the spin coherence time of the SiV center, but to what extent has been largely unknown.

To measure the spin coherence time of a single SiV center, Jelezko and his collaborators [3] and Atatüre and his collaborators [4] performed a technique known as coherent population trapping (CPT), which has been used to study NV centers [9]. The scheme uses two phase-locked laser fields to couple the two ground-state spin states (up and down) to a common excited state (Fig. 2, left). For a given relative phase and amplitude of the two exciting laser fields, the system will be trapped into a "dark state," which is a specific coherent superposition of the two ground states. This dark state cannot be excited optically and photon emission is suppressed, causing a narrow dip in the excitation spectrum when the lasers are tuned to a "two photon resonance" (the point at which a photon can be virtually absorbed and reemitted without energy loss). Since spin decoherence tends to mix the dark state with other states and makes the dip more shallow and broader, one can infer the coherence time between the two spin states from the dip's depth and width (Fig. 2, right). The groups performed CPT on SiV centers in diamond to determine a spin coherence time, $T_2^* \sim 35$ ns[3] and $T_2^* \sim 45$ ns[4] at a temperature of around 4 K. (The asterisk in T_2^* indicates the coherence time was averaged over the time of the measurement.)

The new measurements verify that the SiV center has a spin in its ground state—something that was hinted at by earlier experiments [10]. The work also reveals what mechanisms limit the spin coherence time. Jelezko and his colleagues [3] present evidence indicating that the main culprit is the phonon-induced dynamical JT mechanism. As Atatüre and his colleagues argue, loss of coherence could also come from the fluctuating field produced by defect spins surrounding the SiV center.

Several strategies exist to counteract the contributions to dephasing. The phonon contribution could be reduced by shaping the diamond into a photonic band-gap structure, which would block the dynamic JT effect. Slow magnetic noise could be abated using dynamical decoupling schemes. Another interesting approach would be to replace the silicon-28 atom, which has a nuclear spin of zero, with the silicon-29 isotope, which has a spin-1/2 nucleus, and use the nuclear spin as a long-term quantum memory. Hyperfine levels on silicon-29 have already been identified by Jelezko and his colleagues [3] and methods exist to transfer qubits between electron and nuclear spins [11, 12].

One application for SiV centers in a quantum network would be as quantum repeaters, whose function is to boost the information imprinted on photons. For this purpose, the SiV centers would need to have a spin coherence time approaching milliseconds, like that of the NV center. If this goal is reached, there is indeed hope that SiV centers could be used as a spin-photon interface in a future quantum network.

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About the Author

Guido Burkard

Guido Burkard studied physics at ETH Zurich and received his Ph.D. from the University of Basel, Switzerland. Since 2008, he has been a full professor at the University of Konstanz, Germany. He previously held a faculty position at RWTH Aachen University, and was SNF assistant professor at the University of Basel, after a postdoctoral appointment with the IBM T. J. Watson Research Center at Yorktown Heights, New York. His research interests encompass condensed-matter theory and quantum information, with a focus on spin-based quantum information processing.

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