Nitrogen-Vacancy Centers in Diamond

A solid-state "defect" with applications from nanoscale-MRI to quantum computing

Research into nitrogen-vacancy centers in diamond has exploded in the last decade (see Fig. 1) due to its well-behaved quantum properties, and the ability to monitor and manipulate the quantum state with a combination of microwave fields and laser light.

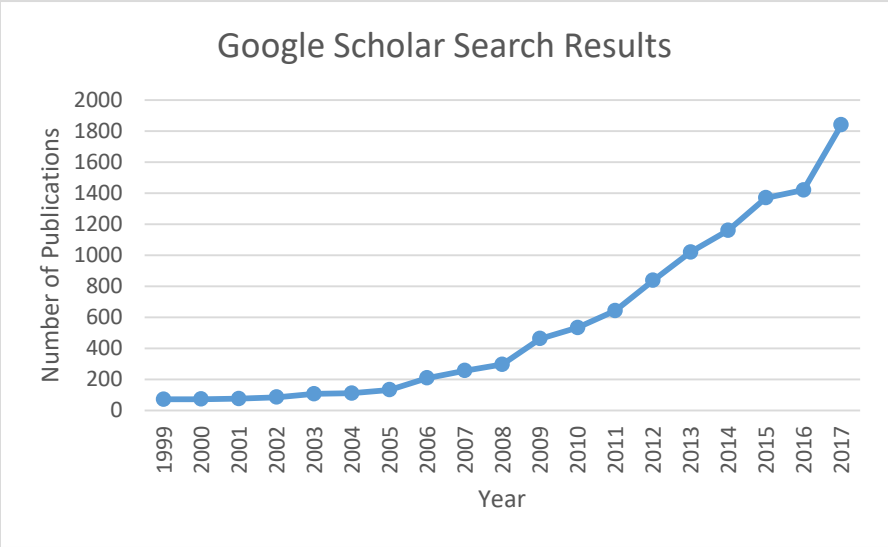

Figure 1. Total publications mentioning "nitrogen vacancy" AND "diamond" by year (Google Scholar).

As its name implies, a nitrogen-vacancy (NV) center (Fig. 2) consists of a nitrogen atom adjacent to a missing carbon atom within a host diamond lattice. The electrons of the dangling bonds at the NV site hybridize to produce a spin-1 system with well-defined energy states and long spin lifetimes, even at room temperature. This permits the spin-manipulation techniques of magnetic resonance—i.e., the application of precisely timed microwave magnetic fields—to manipulate and interrogate the state of the NV spin. That spin state can then be used as a sensor of external environment, since its energy levels are sensitive to external magnetic and electric fields.

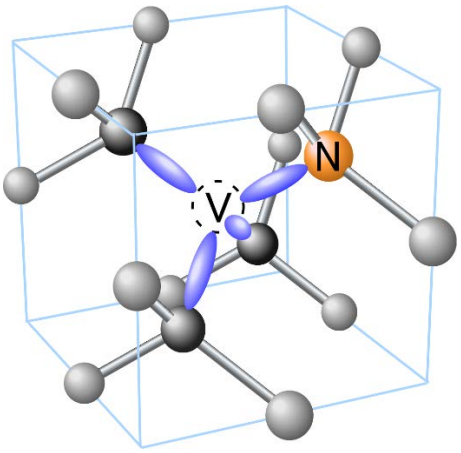

Figure 2. Diamond lattice with an NV site comprised of carbon atoms (gray), nitrogen atom (orange), and adjacent vacancy, with dangling bonds (purple) [1].

The energy states that are monitored in NV experiments are shown in Fig. 3:

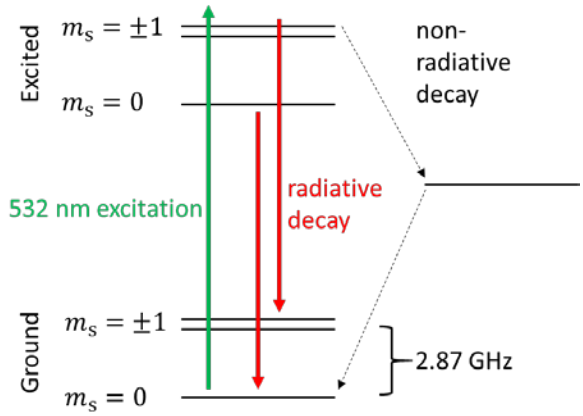

Figure 3. Energy states and transitions of NV center (simplified). Adapted from [2].

Defects in diamond are known for producing color in the otherwise clear crystal (e.g. a nitrogen substitutional defect gives diamond a yellow color, while boron substitutions produce blue). Following excitation with green laser light, the NV can decay via red-light fluorescence at 637 nm. Importantly, the $m_s = \pm 1$ spin states can decay non-radiatively, providing a means for detecting the spin state by monitoring changes in the photo-luminescence. That is, when the spin is excited to the $m_s = \pm 1$ level (using 2.87 GHz microwaves), the red light output of the defect is reduced slightly (Fig. 4(a)). Furthermore, the energy levels of the $m_s = \pm 1$ states are tunable with external magnetic field. By measuring the frequency splitting between the absorption dips (as in Fig. 4(b)), that external field can be measured.

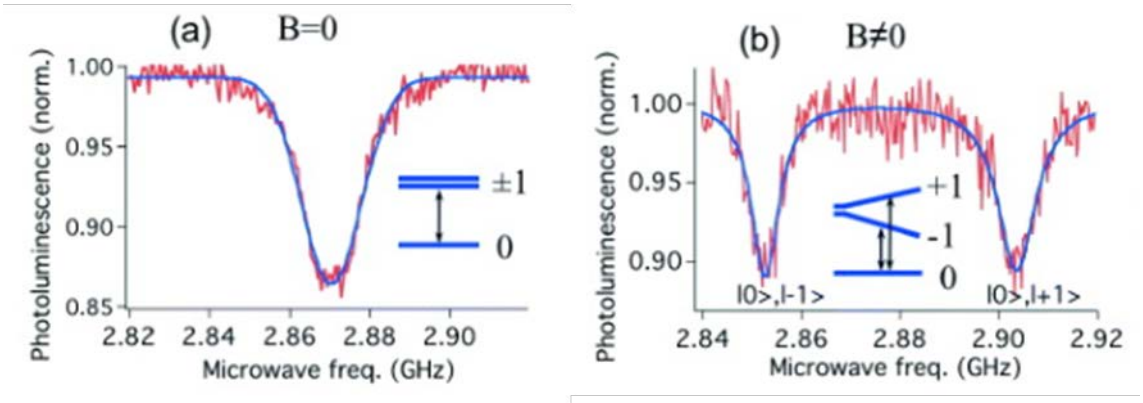

Figure 4. (a) Reduction in photoluminescence under the application of microwaves resonant with the 2.87 GHz transition (between $m_s = 0$ and ± 1 states). (b) Splitting of the $m_s = +1$ and -1 states due to a non-zero magnetic field [3].

Shifts in the energy states can also be caused by external electric fields [4], temperature [5] [6], or strain of the diamond lattice [7], making NV optically-detected magnetic resonance (ODMR) useful for sensing any of these quantities. Because the NV axis can be along any of the 4 crystalline axes of the diamond lattice, 3D vector field sensing can be performed [8]. For example, combined with confocal microscopy techniques to provide spatially resolved mapping of the NV resonance shifts, vector maps of the magnetic fields produced by magnetotactic bacteria have been produced (see Fig. 5) [9].

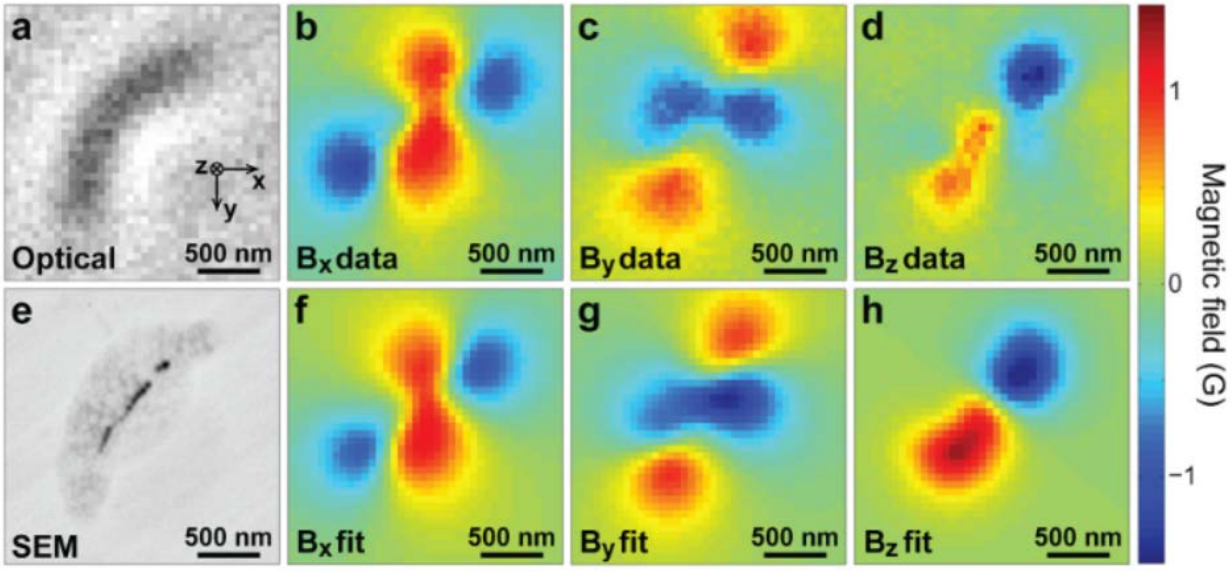

Figure 5. (a) Optical image of magnetotactic bacteria. (e) SEM image of the same bacterium, in which magnetic nanoparticles (black) are clearly visible. (b,c,d) Magnetic field x, y, and z components as determined by NV diamond optically-detected magnetic resonance measurements. (f,g,h) Numerical fits of the measured field distributions (from [9]).

As in most magnetic resonance measurements, the first NV experiments involved large ensembles of the defects. Amazingly however, in samples with low defect density, *individual* NV centers can be isolated and monitored. Because an NV is atomically-sized, this means that the spatial resolution of a single-spin NV sensor is limited only by how closely it can be positioned to the sample of interest. For example, by positioning a single NV center at the tip of an atomic force microscope probe, magnetic domain imaging with 25 nm resolution and 56 $nT/Hz^{-1/2}$ has been demonstrated [10].

Furthermore, the extreme sensitivity and biocompatibility of NV centers (diamond is just carbon, and so exhibits no toxicity), they show particular promise for nanoscale NMR measurements, where the NV center is coupled to the stray field of nuclear spins of organic and biomolecules of interest [11]. NV's are therefore positioned to revolutionize nano-MRI and provide a pathway to 3D images of single molecules under ambient conditions [12]. In fact, single-proton spin detection by an NV center has already been demonstrated [13].

NV field sensing and nanoscale imaging is not limited to static fields. Several groups have now demonstrated NV-based detection and spatial mapping of the time-varying magnetic fields produced by spin waves in ferromagnets [14] [15] or electrical current fluctuations [16] [17].

To further add to the long list of NV applications, the long-lived spin state, manipulability with external fields, and tunable interactions with environment (via lattice engineering) also make them a front-runner for the "qubit"—the unit of information in quantum computing [18].

Quantum computing, like conventional computing, might require separation of long-lived memory bits from fast processing bits. Coupling of a long-lived "memory" qubit (based on either a nearby nitrogen or ^{13}C nuclear spin) to an NV spin [19] [20] [21] could provide exactly this memory and processing architecture. Coherent coupling between superconducting flux qubits (another strong quantum computing candidate) and NV centers has also been demonstrated [22], paving the way to interface between optical and microwave read/write schemes for quantum processing and memory.

Applications utilizing SRS products

Critical to the experimental protocol for optically-detected magnetic resonance in NV diamond is the ability to sweep microwave frequency. It is also useful to execute microwave pulse sequences in order to measure the spin state lifetime. The SRS RF Signal Generators (SG384 and SG386) and Vector Signal Generators (SG394 and SG396) are well-suited for producing microwaves in the frequency-range of interest for NV ODMR studies. Below is a listing of NV-related references making use of SRS products.

1. *Optical magnetic imaging of living cells*
https://www.nature.com/articles/nature12072
equipment used: SG384 (+ amplifier)

1. *Miniature Cavity-Enhanced Diamond Magnetometer*
https://journals.aps.org/prapplied/abstract/10.1103/PhysRevApplied.8.044019
equipment used: SG394 (+ 16W amplifier, circulator)

2. *Microwave-free magnetometry with nitrogen-vacancy centers in diamond*
https://aip.scitation.org/doi/full/10.1063/1.4960171
equipment used: SR865, SIM960

3. *Precision temperature sensing in the presence of magnetic field noise and vice-versa using nitrogen-vacancy centers in diamond*
https://arxiv.org/abs/1802.07224
equipment used: SG394(2x) (+power combiner, switch, and amplifier), SR850

4. *Quantum Control of Nuclear Spins Coupled to Nitrogen-Vacancy Centers in Diamond*
(dissertation, S. Sangtawesin)
Equipment used: SG394 (+ amplifier)

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