Quantum Sensing with Diamonds

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The Objective: Manipulating quantum states is one of the core elements of quantum materials and technologies. Controlling two-level systems – qubits – and creating arbitrary quantum states is one of the main elements of quantum information processing (which includes quantum sensing and quantum computing). The objective of this workshop activity is to manipulate quantum states in a room-temperature qubit, explore practical hardware limitations, and develop strategies to use these states for magnetic field sensing.

The System: The platform for this activity is the nitrogen vacancy (NV) center in diamond. This is a point defect in diamond composed of a substitutional nitrogen atom next to a vacant site (see figure); the important part, however, is that is has a spin degree of freedom we can manipulate as our qubit. We can use microwaves to control the NV center spin and create arbitrary quantum states; this type of spin-based qubit is a very common architecture[1]. In the language of quantum information, one spin state (up) is our $|1\rangle$ bit, another (down) is our $|0\rangle$ bit, and we want to be able to create superpositions ($|0\rangle + e^{i\phi}|1\rangle$) of these states to for sensing, computation, information processing, etc.

One thing that sets the NV center apart from other systems, however, is that it is also *fluorescent*. This serves two purposes: first, the fluorescence depends on the spin state of the NV center, allowing us to read out our state just by looking at how much light is emitted from the sample, and secondly, the optical cycle which gives the fluorescence also relaxes *preferentially into a particular spin sublevel*. This means that just by shining a green laser on our NV center, we can build us an excess of one particular state, which usually requires cooling down to cryogenic temperatures.

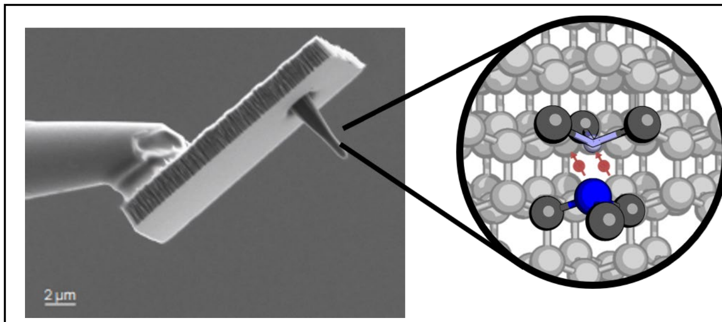

Figure 1 – The NV center is a point defect which acts like an isolated atomic system "caged" by the diamond lattice, allowing us to observe the interesting quantum behavior of atomic systems in a solid-state platform. The samples in this workshop are diamonds which have been fabricated into cantilevers (left) with a single NV center at the pillar apex. In all the measurements, we'll be probing the dynamics of a *single spin*.

The Hardware: For these experiments, we need to be able to access the fluorescence while also manipulating the spin with microwaves. For the former, we use a confocal microscope to image individual NV centers, detecting the very small amount of fluorescence with a single photon detector. To deliver the microwave excitation, we have a shorted wire loop nearby (<50μm) through which we run an AC current. Generating pulses of laser light and microwaves was for a long time

[1] Anasua Chatterjee et al., "Semiconductor Qubits in Practice," *Nature Reviews Physics* 3, no. 3 (March 2021): 157–77, https://doi.org/10.1038/s42254-021-00283-9.

done through the use of solid-state switches; how, however, the advent of field-programmable gate array (FPGA) hardware has enabled direct synthesis of many of the signals, significantly reducing the experimental footprint of these systems.

For our diamond sample, we'll use diamond which has been fabricated into a cantilevered structure. (We usually use this type of system for high-resolution imaging). At the apex of the tip is a single NV center. The fabrication process for this is very involved! Fortunately, as the quantum technology market grows, more and more commercial sources of qubits are being developed. These diamond tips can now be purchased from several sources.

The Experiments: With the background out of the way, let's think about what we require in order to manipulate our quantum states. First, we need to know what microwave frequency to apply. Next, we need to know how long to apply our microwaves for to achieve a particular state. Finally, we need to know how long our qubit can retain information.

(1) Optically-Detected Magnetic Resonance: The first experiment we need to do is optically-detected magnetic resonance (ODMR) to find the microwave frequency where we see a response. The simplest version of this is where we turn on our green laser, apply microwaves, and sweep the microwave frequency, recording our fluorescence at each point.

Questions: How many peaks do you expect, and how many do you see?

(2) Rabi Oscillations: Now that we have a microwave frequency that does something to our spin, we can systematically investigate what happens when we apply it for longer and longer. (This experiment is named after Nobel Laureate Isidor Rabi, who developed this approach in molecular beams[2]) Here, we have a few-microsecond pulse of green light to polarize our qubit, then we apply a microwave pulse of some length (τ), then we apply another green pulse to read out what happened.

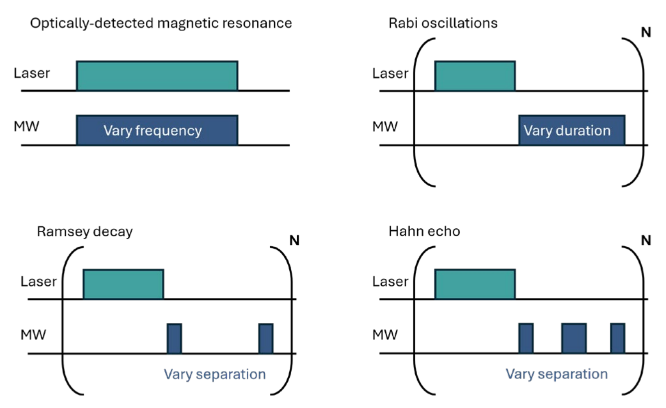

Figure 2 – Pulse sequences for the experiments used in this activity.

Questions: What sort of response do we see? Why does it have this functional form? How does the response change as we change either the frequency or the microwave power? A commonly-used concept is a "π pulse" – what would this refer to in a Rabi experiment?

(3) Ramsey and Hahn Experiments: From the Rabi measurements, we know what parameters to use to create a superposition. How long does this superposition last? We can measure this with a Ramsey experiment: we create a superposition, wait some time, and then try to turn it back into a regular $|0\rangle$ or $|1\rangle$ state. If we vary the delay, we can measure how long this superposition lives for. It

[2] I. I. Rabi et al., "A New Method of Measuring Nuclear Magnetic Moment," *Physical Review* 53, no. 4 (February 15, 1938): 318–318, https://doi.org/10.1103/PhysRev.53.318.

won't turn out to be very long; what we can do to extend this time is use a trick of inserting a π pulse in the middle of this sequence to do a Hahn echo experiment.

Questions: How do the decay times of the Ramsey and Hahn echo measurements compare? What might be limited how long the superposition lives (often called the coherence time)?

(4) Imaging Magnetic Fields: Let's use our system for sensing. Spins are sensitive to magnetic fields (*via* the Zeeman effect). We'll use a sample of a thin magnetic material (1nm thick CoFeB) to demonstrate this by measuring our ODMR spectrum at several points across the sample.

Questions: How can we turn our ODMR measurements into magnetic fields? How could we make our measurements more sensitive?

Further Reading:

C. L. Degen, F. Reinhard, P. Cappellaro, "Quantum sensing", Rev. Mod. Phys., **89**, 035002 (2017)

F. Casola, T. van der Sar, A. Yacoby, "Probing condensed matter physics with magnetometry based on nitrogen-vacancy centers in diamond", Nat. Rev. Mat., **3** 17088 (2018)