Gigahertz dynamics of a strongly driven single spin in diamond

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Nitrogen vacancy (NV) center spins in diamond have emerged as a promising solid-state system for quantum information processing and precision metrology. These isolated spins may be located using confocal microscopy, initialized via optical pumping, and read out through spin dependant photoluminescence measurements. These properties, combined with the millisecond duration spin coherence observed in isotopically purified diamond[1] make this an attractive system for both fundamental investigations of quantum behavior and the development of quantum technologies. Nevertheless, there remain several major challenges to achieve these goals.

Development of diamond NV centers as an individually addressable quantum system has been rapid over the past five years. Starting from the first observation of coherent Rabi oscillations at room temperature in single NV centers[2], there have been several studies of spin control in this system[3,4]. There have also been numerous proof-of-concept demonstrations of coupling to other nearby spins. These include the electronic spin of nitrogen impurities[5] and the nuclear spin of carbon-13[6]. The structure and dynamics of the NV center's orbital excited state has been studied including orbital[7] and spin[8] dynamics. Application of a variety of advanced fluorescence imaging techniques has enabled nanometer-scale resolving power of NV centers[9], allowing interrogation of dipole coupled NV center spins[10]. This approach is one method to scale NV center networks at room temperature. Deliberate placement of NV centers has been developed by combining ion implanting technologies[11] with high-resolution lithography[12]. Another method of scaling involves coupling NV centers via their optical properties at low temperature. This was advanced recently by the demonstration of spin-photon entanglement[13] and non-destructive spin read-out and control using dispersive interactions with light[14]. Efficient use of spin-light coupling will require NV centers that are strongly coupled to optical cavities. Several such efforts are underway, and some success in coupling NV centers to cavity modes has been reported[15]. Efforts to advance diamond NV centers are also directly applicable to its application as a quantum magnetometer. There have been proof-of-concept demonstrations[16] suggesting that NV centers may be competitive with existing room-temperature field sensing technologies in situations that require high spatial resolution.

Performing fast quantum control is crucial due to the practical need for fault tolerance and decoupling of the NV center spin from its environment. Resonant spin manipulation is typically performed under the rotating wave approximation (RWA) which assumes that an oscillating field can be approximated by a rotating field. We present high-speed microwave experiments probing the spin dynamics of single NV centers in diamond driven by a large amplitude oscillating field where this approximation is not valid[3]. We reach this regime by patterning resistively-shorted coplanar waveguides on diamond. These structures allow us to generate an oscillating magnetic field that induces spin rotation on the same timescale as Larmor precession. Coherent spin flips still occur under these conditions, but with sub-nanosecond timescales — faster than expected from the RWA.

Another important challenge is the integration of NV centers with lithographically fabricated structures such as waveguides and cavities to couple them with both microwave and optical frequency electromagnetic radiation. We demonstrate nanofabrication of single NV centers using broad-beam ion implantation through apertures in electron beam lithography resist[12]. This method combines sub-100 nm placement accuracy with high throughput fabrication. Using secondary ion mass spectroscopy and photoluminescence measurements we characterize the depth and lateral profile of the implanted spins.

There are several key challenges for the future. They include:

1. Boosting the optical collection efficiency either through improved geometric collection or integration with an optical cavity/waveguide.
2. Improving the spin and optical coherence times through materials engineering.
3. Improving the NV^- center creation efficiency through optimized ion implantation and annealing.
4. Scaling beyond few-spin systems.
5. Increasing the temperature of spin-photon entanglement to room temperature.
6. Coupling NV center spins to other quantum systems such as superconducting qubits, atoms, etc.

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