

# Quantum Manipulation of Spins in Diamond via Magnetic Field Gradients



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Electronic spins associated with nitrogen-vacancy (NV) centers in diamond (Fig. 1) are a leading platform for nanoscale quantum sensing and imaging<sup>[1]</sup>, as well as quantum computation and simulation in the room-temperature solid state. A key challenge towards these practical applications is to control arrays of proximal NV spins individually and simultaneously. To date, however, individual control of only two NV spins at the nanoscale has been demonstrated.

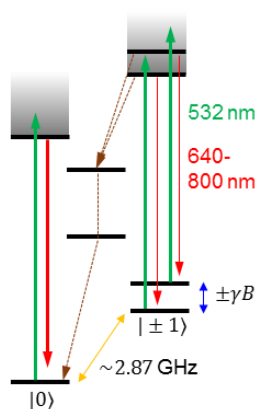


Figure 1: NV energy diagram. The ground states 0 and  $\pm 1$  are split by 2.87 GHz and read out via fluorescence. An external field shifts the  $\pm 1$  states.  $\gamma = 2\pi \times 2.8$  MHz/G is the NV gyromagnetic ratio.

Here we apply nanoscale magnetic resonance techniques, including electrically tunable magnetic field gradients from an electromagnetic coil (microcoil) fabricated with e-beam lithography on the diamond chip (Fig. 2), to realize site-selective addressing and coherent control of a four-site array of NV spins. Sites in the array are separated by  $\sim 100$  nm and contain multiple NVs. The microcoil that we report here produces 0.1 G/nm,  $>100$  times stronger than our previous design did<sup>[2]</sup>.

The strong field gradient splits the resonance frequencies of the NV centers, and thereby

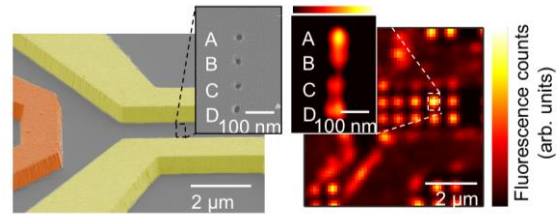


Figure 2: Left: SEM images of microcoil (yellow) and 4-site nanoscale NV array pattern (inset). Right: corresponding confocal image (300 nm resolution) and superresolution image (20 nm resolution) (inset).

enabling selective coherent control of individual nanoscale sites via microwaves whose frequency is tuned to resonance frequencies of the sites of interest (Fig. 3). Our microcoil approach may then provide a promising route for manipulating a nanoscale spin network for quantum information processing and studying nanoscale spin transport under well-controlled environment.

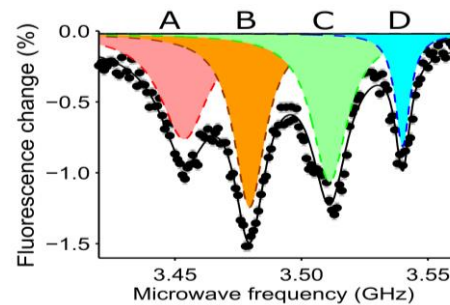


Figure 3: Optically-detected magnetic resonance. The resonance peak splits into four due to magnetic field gradient. Individual sites can be addressed via microwaves with different resonance frequencies.

[1] D. Le Sage\*, K. A.\*, D. Glenn\*, *et al.* *Nature* (2013). [2] K. A.\*, C. Belthangady\*, H. Zhang\*, *et al.* *Nature Nanotechnology* (2015). \*equal contribution