Room Temperature Optically Detected Magnetic Resonance of Single Spins in GaN

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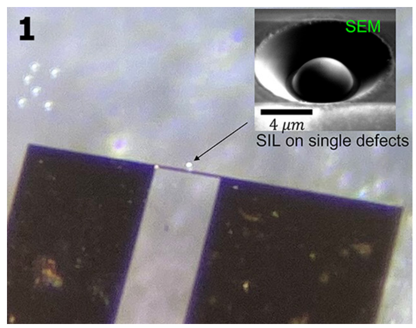
Primary CNF Tools Used: AJA sputtering system, GCA 5x stepper

Abstract:

Optically detected magnetic resonance (ODMR) is an efficient mechanism to readout the spin of solid-state color centers based on spin-dependent relaxation between the optically excited states to the ground states. The detection of high contrast room temperature ODMR becomes the hallmark for a color center to become useful quantum sensors. Our work discovers such optically addressable spins in single defects hosted GaN. We measure two distinct ODMR responses from the defects with contrast as large as 30%, marking the existence of least two defect species in GaN. Our results lay the foundation for a promising quantum sensing platform and provide additional insights into the nature of GaN defects.



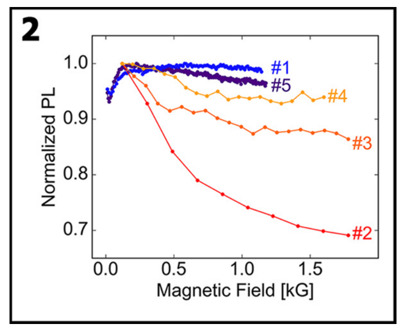


Figure 1, left: Microwave antennae under optical microscope. Inset: SEM of a solid-immersion lens. Figure 2, right: The magnetic field dependent PL of five defects.

Summary of Research:

Background. Room temperature ODMR has been detected in many solid-state color centers such as nitrogen-vacancy (NV) centers in diamond [1], silicon vacancy centers [2] and divacancy centers [3] in SiC, and recently in boron vacancy center ensembles [4,5] and unidentified single defects [6] in hexagonal boron nitride (hBN).

As the third-generation semiconductor, GaN is a mature platform with well-developed electronics applications owing to its wide direct bandgap and high breakdown field [7]. Recently, it has also been found to host bright single photon emitters with spectrally narrow photoluminescence (PL) in the visible spectrum [8,9]. These excellent optical properties, combined with the engineerability of GaN make these single-photon emitting defects attractive for on-chip photonics and relevant quantum technologies. However, the atomic structure of these defects has not yet been identified. We report [10] the discovery of high-contrast optically detected spin resonance, which is both interesting for identifying the defect structure, and for a potential application in quantum magnetometry.

Methods. We use a homebuilt laser scanning confocal microscope to measure the photoluminescence. To enhance the PL collection from the sample, we carve out a hemispherical solid-immersion-lens on top of the defect of interest with focused ion beam milling as seen in Figure 1a. We then use GCA 5x stepper to define the microwave antennae pattern and use the AJA sputter system to deposit a stack of Cr(10nm)/Cu(1um) to make the antennae shown in Figure 1b, which creates microwave that excites the spin resonances.

Results. Figure 2 shows the magnetic field dependent PL (magneto-PL) responses of 5 individual single defects, where the magnetic field is roughly aligned to the GaN crystal c-axis. Defects #1 and #5 show low PL at low magnetic field and saturate at high PL at high field. In

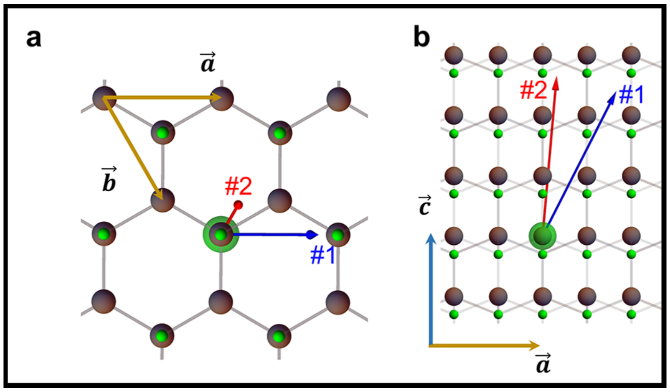


Figure 3: Spin quantization axes of defects #1 and #2 in a GaN lattice.

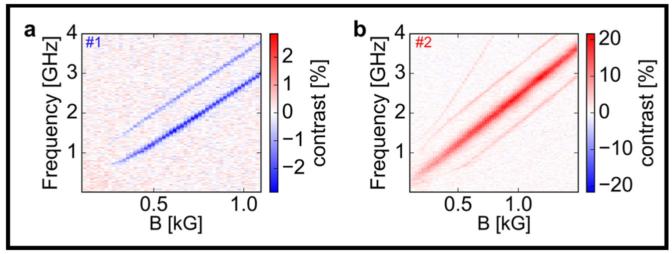


Figure 4: The ODMR spectra as a function of magnetic field of representative defects: defect #1 for group-I and defect #2 for group-II.

contrast, defects #2-#4 show monotonically decreasing PL as the magnetic field increases. The magneto-PL gives the first evidence of two distinct defect species with $S \geq 1$ spin.

The spin quantization axis is an important parameter for studying and revealing the nature of a new defect in solids. We examine the minimum Hamiltonian of a spin with $S \geq 1$ interacting with magnetic field $\vec{B}$ given by

$$H = DS_z^2 + E\left(S_x^2 - S_y^2\right) + g\mu_B \vec{S} \cdot \vec{B},$$

where S is the electronic spin operator, g the electronic g-factor, μ_B the Bohr magneton, D and E together the zero-field interaction parameters. An angle between the magnetic field $\vec{B}$ and the spin quantization axis introduces off-diagonal matrix elements between the spin eigenstates, mixing them and reducing the ODMR contrast. Thus, we find the spin quantization axes by measuring the angle resolved ODMR and finding the optimal angles that produce the largest contrast.

Figure 3 shows the spin quantization axes for defects #1 and #2, both of which lie in the a-plane but do not connect an atom with its n-th nearest neighbor for small n.

We can now further probe the spin Hamiltonian by measuring the magnetic field dependent ODMR, where the field is aligned with the spin axes. Figure 4 shows ODMR spectra of defects #1 and #2 as a function of magnetic field.

Defect #1 exhibits two negative contrast spin resonances that disperse with a gyromagnetic ratio of $\gamma_e = 2.8$ MHz/G, which confirms electron spins. The signal vanishes at low magnetic field because the spin sublevels become degenerate and mix with each other. The data can be fit by $D \approx E \approx 400$ MHz for a spin-1 Hamiltonian.

Defect #2 shows a total of four positive contrast resonances, where three of them disperse with γ_e and one with $2\gamma_e$. Worth noted is that the maximum contrast of the spin resonance of defect #2 is as large as 30%. The number resonances require a minimum model of spin-3/2 system. However, the minimum Hamiltonian can only account correctly for the three resonances that disperse with γ_e when $D \approx 370$ MHz and $E = 0$, pointing to additional terms required in the Hamiltonian.

The ODMR signatures corroborate that there are at least two different species of optically addressable single spin defects in GaN.

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