Key Engineering Materials
ISSN: 1662-9795, Vol. 1056, pp 1-6
doi:10.4028/p-E43pvH
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Submitted: 2025-08-31
Revised: 2025-12-15
Accepted: 2026-02-23
Online: 2026-05-20

Design and Characterization of an ODMR System for NV-Based Quantum Sensing

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Keywords: silicon carbide, optically detected magnetic resonance, nitrogen-vacancy centers, radiation sensing, quantum defects, neutron irradiation.

Abstract. This paper presents the development of a confocal Optically Detected Magnetic Resonance (ODMR) system to study diamond and Silicon Carbide (SiC) for reactor dosimetry and quantum defect analysis. Initially, Nitrogen-Vacancy (NV) centers in diamond were characterized to establish a performance baseline, followed by plans to map and quantify color center populations in SiC crystals before and after alpha and neutron irradiation. By correlating ODMR data with electrical performance metrics, we aim to optimize fabrication and annealing protocols to investigate fast neutron sensitivity. The ODMR system, integrated with a home-built confocal microscopy setup, includes a microwave antenna, magnet, laser, objective, and advanced measurement devices such as Si-APD and Time Tagger 20 for high-resolution T2* and T2 measurements. The characterization of the instrument includes high-resolution fluorescence and ODMR spectra of NV centers in diamond, and improved resolution with confocal optics. Ongoing work focuses on correlating luminescence with reactor neutron fluence and the long-term goal is for the advancing SiC irradiation for integrated spin defect analysis.

1 Introduction

Silicon carbide (SiC) has emerged as a promising material for high-temperature and high dose-rate radiation detectors, due to its exceptional properties such as 10 times higher breakdown voltages and 3 times higher thermal conductivity compared to silicon, as well as suppressed leakage currents in high temperature environments. Beyond its traditional role in power electronics and radiation detection, SiC hosts spin defects, such as silicon vacancies (V_Si) and divacancies, that can function as quantum sensors [1], analogous to the nitrogen-vacancy (NV) centers in diamond. These defects enable sensitive measurements of magnetic fields, and temperature, making SiC a versatile platform for quantum sensing applications.

Our research began with setting up an in-house built optically detected magnetic resonance (ODMR) system to characterize the well-established NV center in diamond as a baseline model. In diamond, carbon atoms form a regular lattice where atomic point defects arise naturally during crystal formation or through irradiation. An NV center consists of a nitrogen atom substituting for a carbon atom, adjacent to a vacancy, forming an NV^- color center when an electron is donated from the lattice [2]. This defect exhibits three ground spin states: m_s = 0 (with strong fluorescence) and m_s = ±1 (with weak fluorescence). Optical pumping with a green laser excites electrons to higher states, while a 2.87 GHz microwave field induces Rabi oscillations, driving transitions to the ±1 levels. These ±1 states, degenerate in the absence of a magnetic field, split via the Zeeman effect when a field is applied, allowing magnetic sensing through changes in photoluminescence. For instance, applying a magnetic field parallel to the [111] crystal axis splits the ±1 states proportionally to the field strength, enabling quantification as B_z = Δf / (2γ), where γ is the gyromagnetic ratio. Temperature shifts in resonance frequencies further enable thermal sensing [3]. Although diamonds host a wide range of color centers, such as N3 (colorless to brownish), H3/H4 (yellow to light green), and 480 nm bands (yellow to orange), the NV center is uniquely suited for quantum sensing because of its spin-

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dependent photoluminescence and controllable energy-level structure.

To characterize these properties, we developed a confocal ODMR system and evaluated its performance on diamond samples. This setup allows for efficient screening of color centers, providing insights into spin state manipulation and sensing capabilities. Although ODMR has thus far been applied to diamond, our ultimate objective is to extend this to SiC, where silicon vacancies and divacancies closely mimic the NV center's behavior. Neutrons can induce such defects in SiC, and intuitively, these defects may enable neutron detection, either through ensemble luminance changes (e.g., yellow-red transitions in diamond analogs) or single-neutron events via spin coherence. As noted in [4] 3C-SiC divacancies have a millisecond Hahn-echo spin coherence time, which is among the longest measured in a naturally isotopic solid.

Our current efforts in irradiating diamond for reactor dosimetry highlight its potential, but SiC offers a lower-cost alternative with significant advantages. Unlike diamond, which lacks mature manufacturing facilities, SiC benefits from established synthetic production (as naturally occurring moissanite is extremely rare) and can be integrated with photonic devices. For example, spin defects can be incorporated into the epitaxial layer of SiC avalanche photodiodes (APDs), enabling an integrated quantum sensing platform via electrically detected magnetic resonance (EDMR) or photoelectrically detected magnetic resonance (PDMR) technique [5]. By advancing from diamond-based ODMR characterization toward SiC-focused development, this work presents our first step for developing scalable, real-world quantum sensors that is aimed to combine detection, readout, and processing in a single material system.

2 ODMR

2.1 System Description

The ODMR system (Figure 1) at The Ohio State University consists of a home-built confocal microscope integrated with a microwave antenna for spin manipulation, an electromagnetic coil to provide a magnetic field for Zeeman splitting, and a 532-nm laser for optical pumping. Fluorescence is collected with a 1.2-NA water-immersion objective and detected on a silicon avalanche photodiode, while a Time Tagger 20 (20 ps resolution) records timing for T2* and T2 measurements [6]. For baseline characterization, we used a 3.0 × 3.0 × 0.3 mm diamond plate containing 1–2 ppm NV centers with ⟨100⟩ orientation, observed through a 550-nm long-pass filter [7].

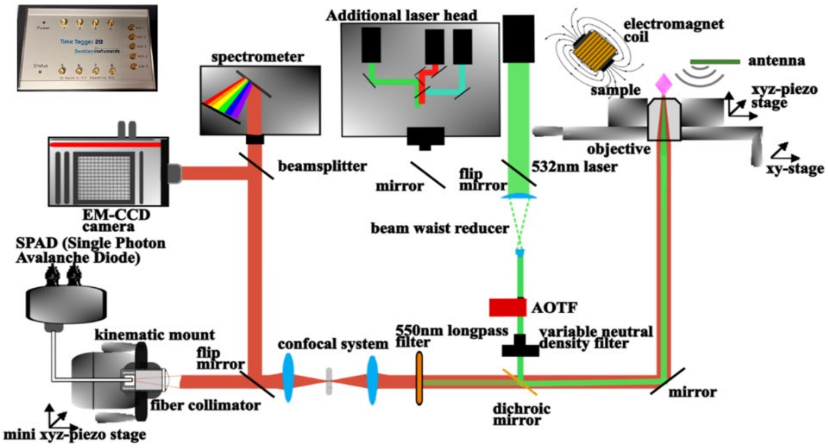

Fig. 1. OSU ODMR light path schematic. From right to left, antenna [8] radiates microwave frequency sequence, piezo stage allows for raster scanning, x-y stage for rough movement, objective to focus laser and collect fluorescence, electromagnetic coil (L = 6.8mH, Ø58 mm, and length = 18mm) to induce Zeeman splitting, dichroic mirror to reflect laser and pass fluorescence, AOTF to allow for laser pulsing, variable neutral filter density filter to control laser intensity, laser to optically pump sample, 550 nm long pass filter to reduce background laser, confocal for higher resolution, spectrometer to collect fluorescence, EM-CCD for imaging NV centers, and SPAD to measure intensity/quantum parameters. The SPAD pulse counter (Time Tagger 20) can be seen in the top left.

2.2 Characterization

The system was tested by exciting the diamond sample with a 5mW 532nm continuous emission laser. Fluorescence spectra and ODMR spectra were collected to observe zero-field splitting and Zeeman splitting. Confocal microscopy was employed to enhance resolution by reducing phonon sideband scattering and to increase axial resolution.

3 Results

The ODMR system successfully characterized NV centers in diamond, producing fluorescence spectra with observable zero-phonon lines (ZPL) and ODMR spectra showing a peak at 2.868 GHz under zero magnetic field (Eq. 1). With an applied magnetic field, Zeeman splitting was observed at 2864 MHz and 2877 MHz, with four-fold splitting corresponding to the [111] NV ensemble crystal axis.

$$D = 2.868\ \text{GHz},\ \ \Delta E = \gamma_e B \qquad (1)$$

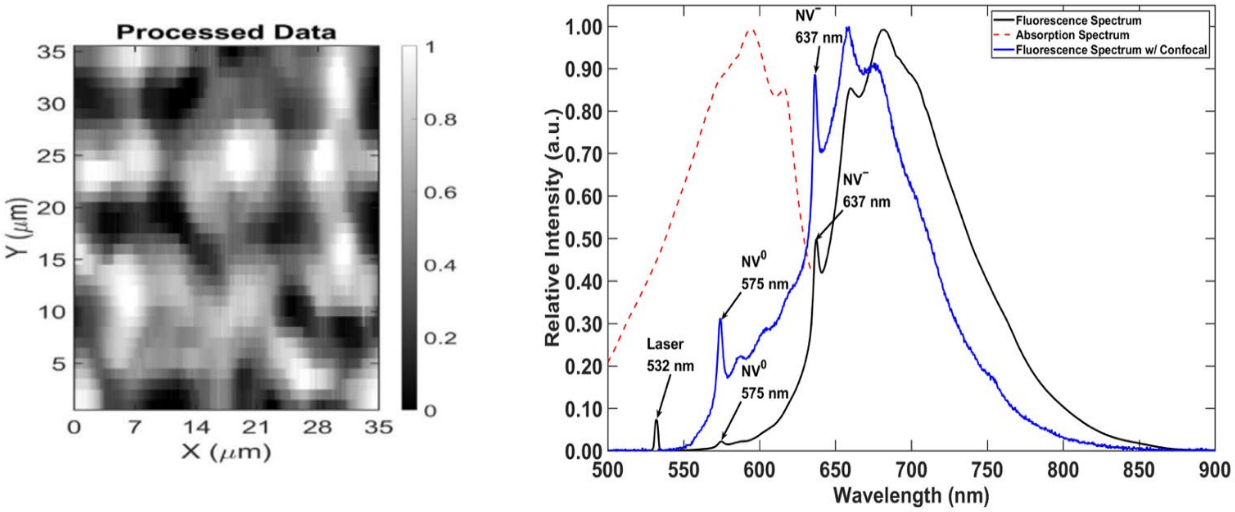

Fig. 2. Scanning fluorescence image of NV rich diamond (left). Fluorescence Spectrum of NV Center in Diamond (right). Black line demonstrates fluorescence collected without confocal system in place. The blue line shows fluorescence spectrum within a confocal volume ($d_{xy} = 324 nm, d_z = 1\ \mu m,\ V = 8.5\ x\ 10^{-16}\ cm^3$).

As seen in Figure 2, the absorption spectrum is (nearly) identical to fluorescence spectrum and is mirrored about Zero Phonon Line (ZPL) [6]. Introducing a confocal lens suppresses much of the phonon sideband emission and rejects out-of-focus light, thereby reducing background scattering from the surrounding lattice and other defects. This results in a lower overall photon count but significantly improves spatial resolution and signal contrast within NV ensembles. In an NV- rich sample (> 200ppm), a single confocal volume contains approximately twenty million NV color centers. Thus, ensemble optical/quantum behavior is measured, and distinguishability of single NV centers becomes impractical. A single crystal grown by chemical vapor deposition with high levels of purity, NV < 0.02ppb, will allow for isolation of individual NV centers and precise determination of their quantum properties. The diffraction-limited lateral full width at half maximum (FWHM) of a single NV center is ~270 nm; therefore, the fluorescence scanning sampling step sizes are set to 100 nm to satisfy the Nyquist sampling criterion. Sigma-clipped frame averaging and z-stacking are used to improve fluorescence image quality, while ODMR resonance behavior are employed to confirm the presence of single NV centers.

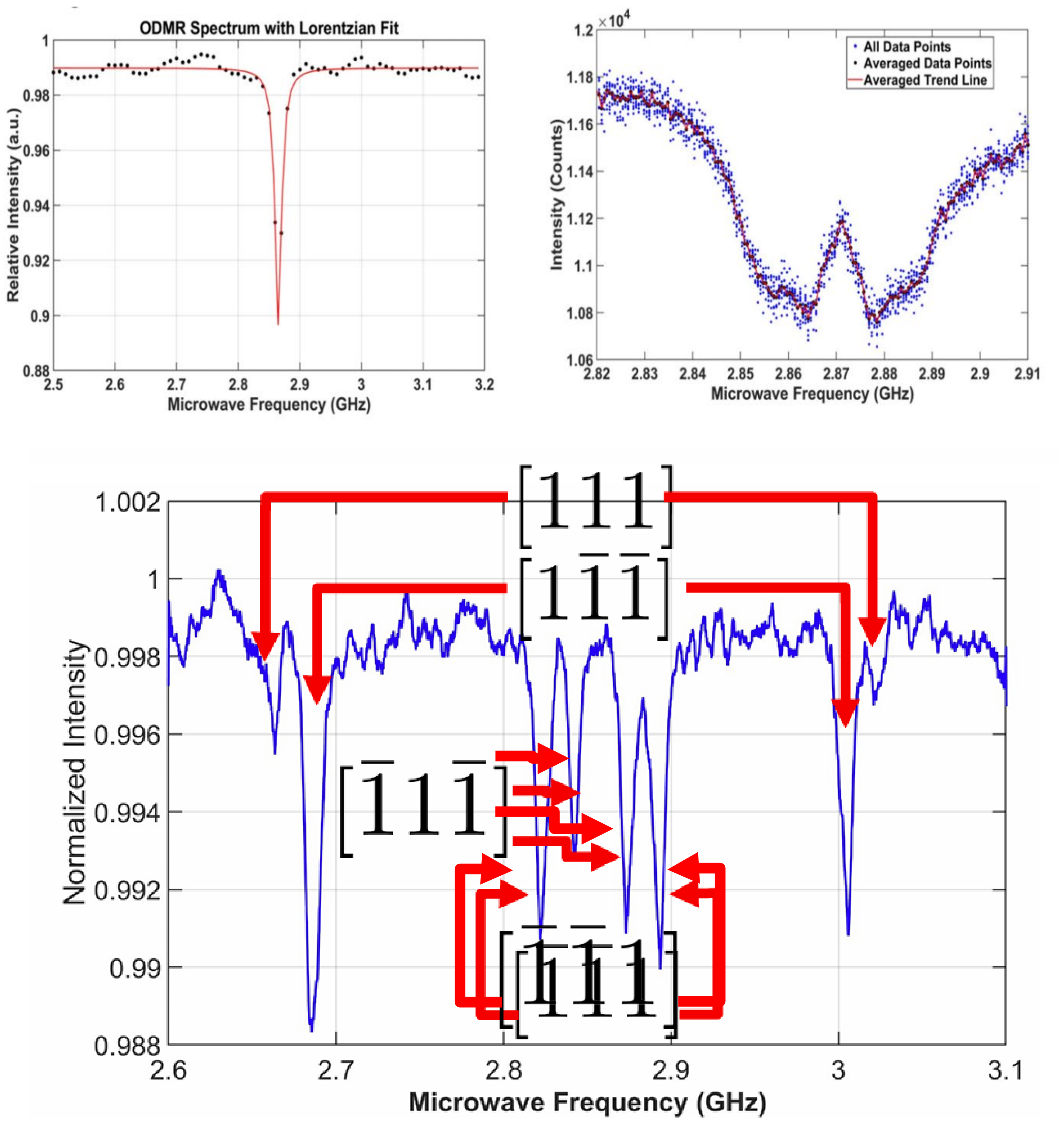

Fig. 3. ODMR Spectrum with Lorentzian Fit and **B**= 0. Microwave frequency was swept in 0.1 GHz increments and relative intensity was measured using integration of fluorescence spectrum. Peak located at 2.868 GHz (Top left). High Resolution ODMR Spectrum of single NV center with **B** > 0 applied. Zeeman splitting is observed. Peaks observed at 2864 MHz and 2877 MHz. 20 points per increment (Top right). ODMR Spectrum with B > 0 aligned approximately to [111] NV ensemble crystal axis. Four-fold splitting is observed, corresponding to 4 crystal axis directions. Further splitting is degenerate and not observable (minimum detectable threshold 0.25%) (bottom).

To characterize the ODMR response of both NV ensembles and single NV centers, measurements were performed under varying magnetic field conditions, as summarized in Figure 3. At zero magnetic field, sweeping the microwave frequency in 0.1 GHz increments produces a single resonance dip at 2.868 GHz, consistent with the expected zero-field splitting of the NV center. When a finite magnetic field is applied to a single NV center, Zeeman splitting becomes evident, yielding two distinct resonances at 2864 MHz and 2877 MHz. These high-resolution measurements, averaged over 20 acquisitions per frequency point, demonstrate the sensitivity of the ODMR technique to small energy-level shifts. For an NV ensemble with the magnetic field aligned approximately along the [111] crystallographic axis, a characteristic fourfold splitting is observed, corresponding to the four possible NV orientations in the diamond lattice. Additional fine structure associated with further sublevel splitting remains below the detectable contrast threshold of 0.25%, which was estimated based on the noise and off-resonance fluoresce signal. Together, these measurements validate the system's ability to resolve both ensemble and single-NV spin transitions across a range of magnetic field conditions.

The neutrally charged NV^0 (NV^- without electron) does not produce ODMR signal, but does emit fluorescence, confounding the active center signal. The NV^0 presence necessitates for a method to differentiate the opposing color center fluorescence signals. Undesirable color centers can be distinguished by simultaneously measuring ODMR response and fluorescence, allowing each color center to be mapped according to its type. Similarly, in SiC, multiple fluorescence emitting color centers exist, varying the charge state and spin properties of the material. The ODMR system presented successfully differentiates NV^- from NV^0, allowing for accurate mapping of spin defect centers and providing a methodology for more complex materials such as SiC.

4 Discussion

The results confirm the efficacy of our newly built ODMR system in characterizing NV centers in diamond, providing a baseline for continuing SiC studies. The observed Zeeman splitting and four-fold splitting align with theoretical expectations for NV centers (5). SiC Schottky diodes exhibited promising stability at high temperatures, making them suitable for reactor dosimetry. The confocal system's ability to reduce background scattering enhances the resolution of fluorescence measurements, critical for quantum defect analysis. The current setup focuses on NV-diamond measurements but is designed with modularity to enable future extension to SiC-based defects. Detecting and addressing V_{Si} centers in SiC is substantially more challenging, even with optimized high-contrast samples, making it important to understand the minimum ODMR contrast that this system can reliably detect. We estimate the lower detectable contrast boundary using $C = k (\sigma / I_0)$, where I_0 is the mean off-resonance fluorescence, σ is its RMS noise, and k is the required signal-to-noise ratio (taken as 5 for a conservative criterion). Based on this analysis, the minimum detectable ODMR contrast for our setup is set at 0.25%.

5 Conclusion and Future Work

This study developed a confocal ODMR system to characterize NV centers in diamond, achieving high-resolution fluorescence and ODMR spectra. Future work includes irradiating diamond and SiC to correlate luminescence with reactor fluence, performing T2 measurements on single NV centers, and developing SiC sensors with integrated spin defect readouts.

Acknowledgments

We thank Dr. Jennifer Choy and Dr. Ricardo Vidrio for providing the microwave antenna and for constructive discussions. Dr. Raymond Cao acknowledges Dr. Takeshi Ohshima, Dr. Shinobu Onoda, Dr. Yuta Masuyama, and Dr. Shinichiro Sato for discussions and suggestions.

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