NV Centres in Diamond for Magnetic Field Quantum Sensing

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ABSTRACT

Nitrogen-Vacancy (NV) centres in diamond have been shown to possess a quantised energy structure that allows for a number of macroscopic parameters to be measured with a high level of sensitivity. The process of sensing magnetic fields can be achieved through the behaviour of the NV centre's electron spin triplet states using the separation of field-dependent and independent states, inferred by applying a microwave frequency to drive transitions. Observation of the states is achieved through optical pumping and stimulated emission, where the intensity of the fluorescent emission and frequency of the applied microwaves relates to the magnitude of the magnetic field the NV centre experiences. The optical method of sensing can be facilitated using optical fibres in which NV diamond particles are embedded between the core and outer fibre layers, leading to a robust platform for further practical applications with strong resistance to external interference.

Keywords: quantum sensors, magnetic sensing, NV centres, ODMR

1. INTRODUCTION

Optical methods for measuring magnetic fields are important as they are generally sensitive, immune to electromagnetic interference, small in scale and can transmit signals over long distances. A quantum sensing approach to the measurement of magnetic field strength is the basis of this work, given the importance of this parameter in many industries, including automotive, aviation, food, and mining and in MRI scanning systems, for example. Quantum sensing is the application of observing quantum phenomena for measurements of macroscopic parameters. The advantage of many quantum sensor designs over traditional sensing technology is often the significant improvement in sensitivity. Nitrogen-Vacancy (NV) centres in diamond are a popular method of implementing quantum sensing, for the high sensitivity, the multiple measurable quantities including electric fields, magnetic fields, stress, and temperature, and the minimal operating requirements compared to other quantum sensors such as SQUIDs, the current best quantum magnetometers [1, 2]. NV centres are defects in the diamond structure where two adjacent carbon atoms have been replaced with a nitrogen atom and a vacant space, shown in Figure 1.

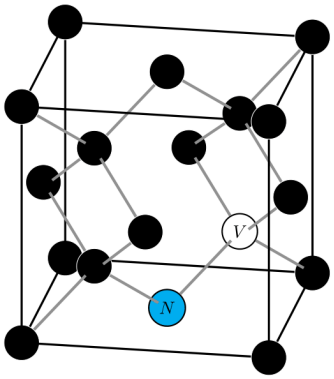

Figure 1: Unit cell of diamond with an NV centre defect. Two carbon atoms are replaced by the nitrogen and vacancy. There are four potential orientations of the NV centres in the diamond lattice.

The three unbound electrons of the neighbouring carbon atoms gather in the vacancy, two of which form a quasi-covalent pair, leaving a single free electron for a spin quantum number $S = 1/2$ system. Through nitrogen defects in other parts of the diamond, an additional electron is often donated to the NV centre, leading to the charged state NV^- and an $S = 1$ system. This is the commonly used form of the centre for quantum sensing.

2. ENERGY STRUCTURE

A simplified diagram of the energy levels produced by the charged NV^- centre defect is presented in Figure 2, which shows the structure that allows magnetic sensing. The ground state ${}^3A_2$ has the possible electron spin orientations $m_S = 0, \pm 1$. There is the higher energy state ${}^3E$ to which electrons can be excited to optically through 532 nm laser light. This excitation preserves the spin orientation as they undergo this change in energy. The relaxation process back to the ground state for the excited $|{}^3E, 0\rangle$ state is dominated by the fluorescence of red light; hence emission from the centre is stimulated by the applied 532 nm light. The $|{}^3E, \pm 1\rangle$ state also relaxes by fluorescence, but there is a significant proportion of spins that relax through a meta-stable state. Unlike the emitting paths, this mechanism does not maintain the orientations, and the spins preferentially relax to the $|{}^3A_2, 0\rangle$ state. Repeated cycles of optical excitation pump the spins into a polarised condition in $|{}^3A_2, 0\rangle$. Because the relaxation of $|0\rangle$ is dominated by the radiative path, optical pumping leads to an increase in the fluorescence as the population of $|{}^3A_2, 0\rangle$ increases, up to a maximum saturation [1].

The electron behaviour in the ground state of the NV^- centres, isolated from the laser excitation, can be described by the following Hamiltonian [1]:

$$\mathcal{H} = D\left(\hat{S}_z^2 - \frac{2}{3}\right) + E\left(\hat{S}_x^2 - \hat{S}_y^2\right) + g\mu_B \vec{B} \cdot \vec{S} \tag{1}$$

where the first term represents the longitudinal zero-field splitting with constant D, the second term the transverse zero-field splitting with constant E, and final term the Zeeman effect on the electron spins. $\hat{S}_{x,y,z}$ represents the spin operators in x, y, and z, g is the g-factor for electrons in this system, and μ_B the Bohr magneton constant.

$D \approx 2.87$ GHz$/h$, while E is negligible in comparison. Under a zero-field condition $\vec{B} = 0$ the longitudinal zero-field splitting is the only major contribution. Due to the $\hat{S}_z^2$ term, the ± 1 states are degenerate, and so D represents the separation between $|0\rangle$ and $|\pm 1\rangle$ in the ground state. Under a $\vec{B} = B_0\,\hat{z} \neq 0$ condition, the $|\pm 1\rangle$ levels split according to $g\mu_B B_0 m_S$. The separation of each state from $|0\rangle$ is now shifted away from D to two values, $D \pm g\mu_B B_0$ [1].

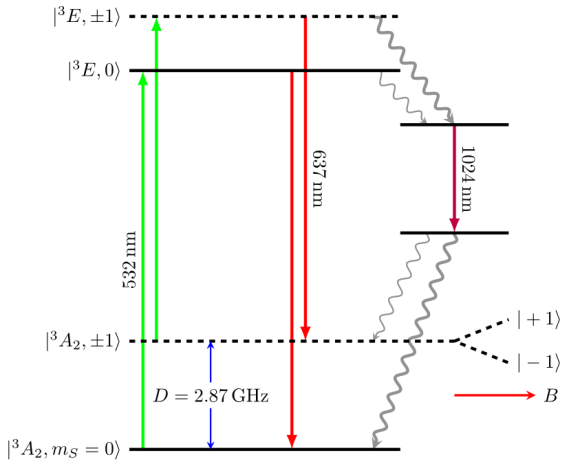

Figure 2: Energy levels of the NV^- centres in diamond. The available spin states are $m_S = 0$ and ± 1. A 532 nm laser excites ground state electrons to a higher state while preserving the m_S spin orientation. The relaxation paths can be either fluorescent or non-radiative, and the proportions for which depends on the initial m_S value.

3. MAGNETIC SENSING

The application of magnetic sensing comes from that change of separation through the Zeeman splitting term. The shift away from D is directly proportional to the magnetic field B_0. Were the energy absorbed from driving transitions from $|0\rangle$ to $|\pm1\rangle$ at frequency 2.87 GHz to be measured, the application of a magnetic field would show a reduction in energy absorbed by the NV^- centres as the magnetic field increases. A search in frequency for the maximum energy loss would reveal the new separation, and hence the magnetic field can be inferred. This is the foundational idea of magnetic field sensing using NV^- centres.

The mechanism for observing the maximum absorption is rooted in the optical pumping described. As already explained, applying laser light onto the centres will stimulate and increase fluorescence over time up to a maximum saturation of the $|^3A_2, 0\rangle$ level and relaxation processes. Applying 2.87 GHz under zero-field will lead to a drop in the fluorescence as the polarisation is broken and electrons leave the $|^3A_2, 0\rangle$ level, follow the $|^3A_2, \pm1\rangle$ excitation path, and more electrons relax via the non-radiative mechanism. The effect this has on the fluorescent emission is near-instantaneous, as the decay time for the excited spins via photoemission is of the order of ~ 10 ns [3]. Under a non-zero field, this will still occur, only now at the two new separations for $|^3A_2, +1\rangle$ and $|^3A_2, -1\rangle$. There is now a method of observing the separation through the frequencies at which there is a reduction in output fluorescence. This technique is called optically detected magnetic resonance (ODMR). A simple ODMR setup is shown in Figure 3. The effect of field on a frequency sweep is illustrated in Figure 4, and also how the field can be inferred from the separation of resonances and the Zeeman effect term in the Hamiltonian.

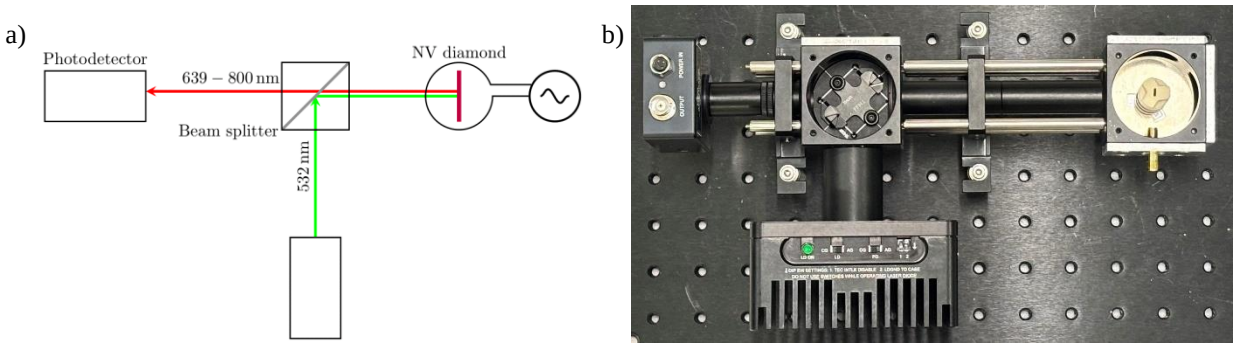

Figure 3: A basic ODMR spectrometer. Laser light of 532 nm is emitted and reflected by a beam splitter towards the NV^- diamond sample. The emitted red fluorescence passes through the beam splitter to be measured by a photodetector

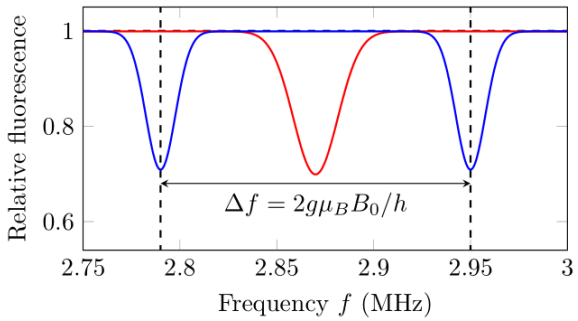

Figure 4: Typical ODMR observation of NV^- centres. With zero-field (red) the resonances are equivalent at a single peak for $f = 2.87$ GHz. With an applied field (blue) the levels split into two resonances with spacing equivalent to the energy gap, proportional to the field B_0.

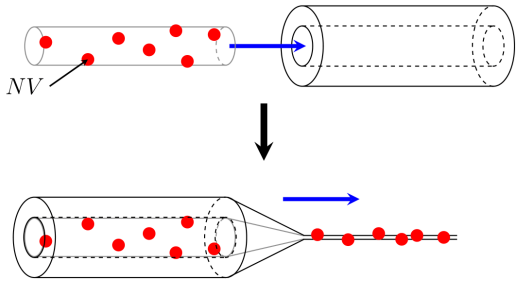

Figure 5: The process of embedding NV centres containing diamond particles into an optical fibre, where the inner rod is coated in NV diamonds, inserted into the tube, then drawn into a fibre.

The ODMR setup can be adapted to measure magnetic fields, usually through applying two singular frequencies near the two separate resonances and a feedback loop to fix to the maximum drop in fluorescence. The resonances are typically very sharp. These can typically achieve sensitivities on the scale of $1 - 10$ nT$/\sqrt{\text{Hz}}$ or lower depending on the material and techniques applied [4,5]. An optical fibre configuration of the approach can be envisaged by embedding the NV^- centres in a fibre. This has been achieved by coating a glass rod in NV centre diamond particles of ~ 1 μm diameter, passing it through an outer tube to make a preform for the optical fibre, which is then drawn into the fibre. This creates a long fibre with many diamonds embedded at the interface between the core and outer layer. Such embedded centres have shown sensitivities of 350 nT$/\sqrt{\text{Hz}}$ [6]. The process is shown in Figure 5

4. CONCLUSION

The applications of magnetic sensing with NV^- centres are driven mainly by the high sensitivity, but other benefits are to be found. Research has applied NV^- centres to magnetocardiography for non-invasive and more sensitive heartbeat observations [7], precise monitoring on the charge state of electric vehicle batteries with no interference to the main circuitry [8], and there continue to be improvements to the versatility of its magnetometry, with vector field sensing through the four NV orientations in the diamond [9]. The use of optical readout opens it to an optical fibre configuration, as illustrated. These techniques provide a foundation for applying NV centre sensitivity to robust optical fibres and offers potential uses outside rigidly controlled laboratory conditions, moving into real-world applications.

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