Magnetic field sensing with color centers in a wide-bandgap semiconductor

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Abstract

Recent advancements in the control and readout of color centers in wide-bandgap semiconductors have enable the possibility of using such systems in magnetic sensing applications with great sensitivity and spatial resolution. Particularly, the atomic-sized nitrogen-vacancy center in diamond has high potential due to its magnetic field-dependent electronic structure and wide range of operating conditions. Furthermore, diamond's non-toxicity makes it a great prospect for biomedical sensor applications. This article will present a magnetic sensing protocol using optical readout and microwave control of the nitrogen-vacancy center. The optically detected magnetic resonant signature of the color center is theoretically simulated and analyzed to deduce the magnetic field from the Zeeman Effect. The magnetic field coupling to the spin's energy is then quantified according to the defect orientation relative to the field direction.

Keywords: magnetic field sensor, nanosensor, diamond, nitrogen-vacancy center, semiconductor, biosensor

1. Introduction

Magnetic field sensing is one of the necessary fundamental measurements in electrical engineering and material engineering. Conventional magnetic field sensors, such as Hall probe sensors [1], microelectromechanical (MEMs) devices [2], and loop antenna, rely on direct electrical measurements. Unfortunately, the random nature of electron's motion creates a noise floor, which limits the sensitivity of the measurement to the so-called classical limit. There are a few existing novel techniques that utilize quantum systems to overcome the classical limits, such as superconducting quantum interference devices (SQUID) [3], atomic vapor cell magnetometer [4]. Despite exquisite field sensitivity [3, 4], the sensor spatial resolution is rather limited preventing these sensors from studying nanoscale magnetic features.

Recently, magnetic field sensing using color centers in semiconductor becomes a new topic of interest. The optical readout nature of the color center allows for non-invasive field measurement without the need for direct electrical measurement. Particularly, the nitrogen-vacancy (NV) center color defect in diamond has an electronic structure that couples to magnetic field [5]. The quantum nature and the atomic-scale system size allow the possibility of achieving simultaneous high sensitivity and spatial resolution. Additionally, diamond's nontoxicity and chemical inertness open doors to using NV centers in wide range of conditions, including in solutions and in live biological systems. Furthermore, NV centers have been found to be stable in extreme temperature ranging from 4K to 600K [6]. This article will discuss the underlying theory of the magnetic field sensing mechanism and propose a protocol for practical magnetic sensing applications. In contrast to the expensive aesthetic diamond gems, diamond sensors can be made from waste diamond particle, which is the by-product from gems cutting. This possibility along with other material suggestions will be discussed. Although there are a few sophisticated theoretical works on NV center available, the goal here is to provide experimentally oriented analysis and calculation in addition to other complicated theoretical NV center treatments.

2. Methodology

2.1 Basic mechanism

NV center is a solid state defect in diamond, which consists of an adjacent pair of nitrogen and vacancy replacing a pair of carbon atoms in the diamond lattice, as shown in Figure 1. Since nitrogen is an abundant element in the environment, NV centers already occur naturally in diamond. The defect density can also be artificially controlled by nitrogen doping process. NV center can be excited with a green laser and will consequently emits light in the red wavelength range. The ground state of

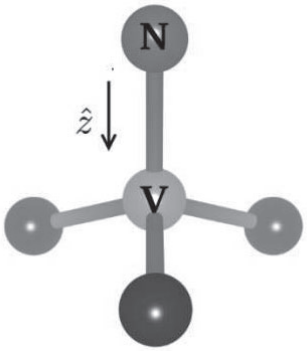

Figure 1 Nitrogen-vacancy center in a diamond structure replacing carbon atoms (blue).

the defect is a spin-1 system, with energy gap in the microwave region. The RF field can be used to readily control the defect. The NV center is hosted in diamond, which is a semiconductor with a large 5.5 eV bandgap. This makes the NV center stable from the environment. Additionally, the diamond has extremely high Debye temperature, isolating the NV center from thermal phonon noises.

Interestingly, the energy gap between the |+1> and |-1> spin states couple to the magnetic field [5] via Zeeman Effect, as shown in Figure 2. Additionally, the NV center has a spin dependence fluorescence emission rate, where the decay of |0> from the excited states is brighter than the decay of |+1> and |-1> spin states due to metastable state mechanisms [5]. Hence, the spin energy spectra measurements can be used to analyze the magnetic field being sense at the NV center. Because of the angstrom-scale size, the NV center also have possibility of detecting magnetic field features with nanometer scale resolutions.

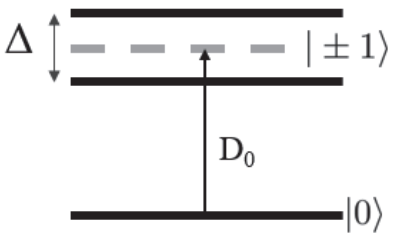

Figure 2 Energy diagram of the NV center's ground state. The magnetic field splits the previously degenerate |+1> and |-1> spin states.

2.2 Measurement protocol

Diamond substrates are the most common form of material for NV center experiments. Nevertheless, nanodiamond can be used in similar ways [7]. The diamond samples are commonly prepared with ion-implantation technique to have defect density near 1 defect/μm2. This is such that individual NV centers can be resolved within the optical limits. High temperature annealing above 800 C is then needed to form nitrogen-vacancy centers. As a final step, the diamond is cleaned in an equal mixture of boiling perchloric, sulfuric and nitric acid mixture to remove the graphite layer.

The nitrogen vacancy center can then be imaged using a confocal microscope with a 532-nm excitation laser. A microwave field is applied to obtain the spin resonant signature. The microwave frequency is swept near 2.87 GHz, to find the electron spin resonances. These are standard operation for NV center measurements which can be referred to many well documented literatures [8]. The zero-field spin resonance at 2.87 GHz is a result of the intrinsic spin-spin interaction. The fluorescence emission of the NV center is dependent on the spin state. Hence, the spin resonance signature is obtained from a reduction in the fluorescence emission. With no magnetic field, the |+1> and |-1> spin states are degenerate states. However, in a magnetic field, the spin states will be splitted as discussed later in the theoretical analysis.

2.3 Magnetic field sensing

For calibration, a known magnetic field can be introduced into the setup. The |+1> and |-1> spin states will be split with the Zeeman effect from the magnetic field. Hence, two dips in the resonance spectroscopy is shown in the simulated resonance response in Figure 3, where the center of the plot is 2.87 GHz with ± 50 MHz scanning window. The size of the splitting is directly related to the magnetic field along the NV center axis, which will be discussed in the next section. This result from the simple technique can then be used to analyze for the magnetic field magnitude at the NV center's location.

3. Theoretical analysis

The magnitude of the magnetic field at the NV center can be analyzed by considering the energy Hamiltonian of the system in the spin-1 basis with magnetic field consideration

$$H = D_0 S^2_z + g\mu_B \mathbf{S}\cdot\mathbf{B} \quad (1)$$

where D_0 is the zero-field splitting, g is the electron g-factor, and μ_B is the Bohr magneton and S_i are the Pauli spin matrices. This Hamiltonian can be diagonalized to find the energy levels as affected by the magnetic field. The solution can be written as

$$E_{\pm} = D_0 \pm g\mu_B B_z \quad (2)$$

where B_z is the magnetic field along the NV center's axis. The equation can be simplified further for data analysis by introducing the splitting term $\Delta = E_+ - E_-$. The splitting term can then be calculated as,

$$\Delta = 2\, g\mu_B B_z \quad (3)$$

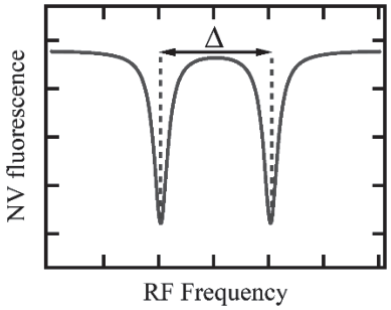

Figure 3 Simulated electron spin resonance signal under magnetic field

For simplicity, a new variable can be defined as a proportional constant, $\gamma = g\mu_B$. From the analysis above, we can precisely calculate the magnetic field sensitivity conversion to be 2.799 MHz/gauss, using the known value of the electron g-factor and Bohr magneton. This magnetic field sensitivity constant can be used to analyze the magnetic field from the spitting as follows,

$$B_z = \Delta / (2.799 \text{ MHz/gauss}) \quad (4)$$

To analyze the spin-resonance data, the Fourier spectrum of the sinusoidal microwave field interaction with the spin is considered. As a result, the electron spin resonance signature can be fitted with a multi-peak Lorentzian functions to extract the splitting;

$$s_i(\omega) = -A\frac{\alpha}{\alpha^2 + (\omega - \omega_i)^2} + B \quad (5)$$

where A and B are fitting constants, and α is the width of the resonance peaks. The linewidth can then be used to calculate the magnetic field sensitivity of a specific NV center, which can be typically estimate to be under μT-per-$Hz^{1/2}$. For better sensitivity, the spectral linewidth can be improved by controlling the amount of impurities and lattice defects in the diamond crystal. With more sophisticated quantum dynamical decoupling, the diamond sensor can be made to have sensitivity under pT-per-$Hz^{1/2}$ [9]. There are four possible NV center orientations according to the carbon bonds in the diamond structure. To obtain the direction of the field, a few other NV centers with different orientation in the diamond crystal has to be considered. Simple vector analysis can be used to project the magnetic field on to the four NV center's orientation in the diamond unit vector axes (a_1, a_2, a_3, a_4). The splitting caused by a magnetic field in an arbitrary direction can be calculated as,

$$\Delta_i = 2\, g\mu_B \mathbf{B}\cdot\mathbf{a}_i \quad (3)$$

The magnitude and direction of the field can then be vectorially reconstructed from the measurements.

4. Conclusion

This article described the possibility and the protocol to perform magnetic field sensing with NV center spin in diamond. Additionally, the fundamental analysis of the theoretical framework was presented. Diamond is known to be nontoxic and compatible in extreme conditions as well as in biological systems. Diamond sensor should be useful for many biomedical applications, such as in neuron cells, where electromagnetic signal is involved. The NV center can in principle serve as a fluorescence biomarker with great photostability. The added ability to probe magnetic field should give more insight in the biological system dynamic compare to the conventional biomarkers. NV center also has the advantage of both sensitivity and spatial resolution, which could be useful in some intricate systems.

Nevertheless, diamond is still viewed as expensive material compare to other semiconductor devices. However, the magnetic sensing only requires extremely small particles of diamond, since the defect is only about the size of a few atoms. These small diamond particles can be cheaply synthesized from detonation

process. Additionally, the waste from the jewel cutting industry can also be reclaimed to use as magnetic sensor. These diamond particle approaches could provide a new gateway toward more accessible diamond sensors.

In conclusion, this article has presented a protocol and theoretical model analysis for magnetic sensing applications using diamond. The information here should be an important fundamental element toward the establishment of magnetic sensing with diamond. Additionally, the promising possibility of applications in biological applications was proposed. Finally, the alternative material routes for realizing diamond sensors were also suggested.

5. Acknowledgments

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