

Single Spin Detection

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ABSTRACT

There have been significant advancements towards developing the ability to detect the spin of a single particle within the last decade. The fundamental challenge in achieving single-spin sensitivity is accurate measurements from a single spin, which are extremely small and on the order of a few attonewtons for an electron spin. Recently, single-spin detection has been accomplished with the development of several innovative techniques, enhanced insights in the relevant spin relaxation processes, and the successful detection of statistical polarization in small spin ensembles. This paper aims to review some of the current approaches that have been applied for single spin detection and their applications.

INTRODUCTION

Spin is a fundamental property of all elementary particles and is typically viewed as the intrinsic angular momentum. Both electrons and nuclei possess spin, and these spins precess around the direction defined by an applied magnetic field. Additionally, the frequency of precession scales with the applied field and is roughly 1,000 times faster for electrons. Traditional approaches to spin detection are based on electron spin resonance (ESR), where an applied static magnetic field causes the spins of a sample to align with the field. Some of the spins will align parallel or anti-parallel to the field and the difference in energy between the two

states is called the Zeeman energy (i.e. their frequency is the Larmor frequency). Simply by monitoring the absorption at a given frequency and as a function of applied magnetic field strength, we can extract information about the nature of spins in a sample. This approach however, requires a large number (10^{10} - 10^{15}) of spins for a measurable signal. While, ensembles of spins have found use in a variety of applications from magnetic resonance imaging to magneto-electronic devices¹, we have become very interested in single spins, which ultimately promise the creation of nanoscale electronics, imaging the three-dimensional structure of molecules and quantum computing². These new developments will inherently require single-spin detection technology, both for the readout of quantum states and for device characterization. Since much of current information on particle spins is derived from ensemble measurements, there have been substantial efforts within the last decade to develop new tools to monitor and manipulate single spins. Sensing single spin states has been achieved through both optical techniques^{3,4,5,6}, and electrical sensing techniques^{7,8,9}. Single-spin detection has also progressed through better understanding of relevant spin relaxation processes^{10,11} and successful detection of statistical polarization in small spin ensembles¹². In the following sections, this paper will review the some of the current approaches that have been applied towards single spin detection and their applications.

OPTICAL DETECTION TECHNIQUES

Optical detection of single spins has been realized using several modes including magnetic resonance force microscopy (MRFM), quantum dots, nitrogen-vacancy defects in diamond and scanning tunneling microscopy. MRFM combines the use of three-dimensional magnetic resonance imaging (MRI) and atomic force microscopy (AFM) for a system with

detection sensitivity to the single spin level. The basis of MFRM is a flexible cantilever with a ferromagnetic tip that senses a magnetic force exerted by the spins in a sample. The fundamental elements of the MFRM system are shown in Fig. 1 below and are a mass-loaded silicon cantilever with an attached 150-nm-wide samarium-cobalt magnetic tip. The measured sample is vitreous silica that was irradiated with a 2-Gy dose of Co^{60} gamma rays, so a low density of electron spins was present. The experiment was performed in very low operating temperatures (1.6K) to minimize the force noise and reduce the relaxation rate of the spins. The SmCo magnetic tip is mounted above the sample and generates a large magnetic field gradient into the treated mica (approximately proportional to its magnetization divided by its diameter). In the presence of the field gradient, the applied oscillating magnetic field excites electrons at a particular depth in the sample at their resonant frequency. The field gradient also induces spins located at different depths beneath the tip to resonate at different frequencies, providing selective excitation of spins and in turn, high resolution imaging. The vibration of the cantilever causes the resonant slice to sweep back & forth and when the slice finds a spin, the resonance repeatedly flipped the spin of the electron, giving the cantilever a slight boost and pinpointing the location of the spin responsible for the signal. The change in frequency of the cantilever is read by a laser interferometer, just as in atomic force microscopy, and translated to measurements by a computer. To locate spin signals, the sample was scanned through many independent locations, before a strong signal from a well-positioned spin was found and measured.

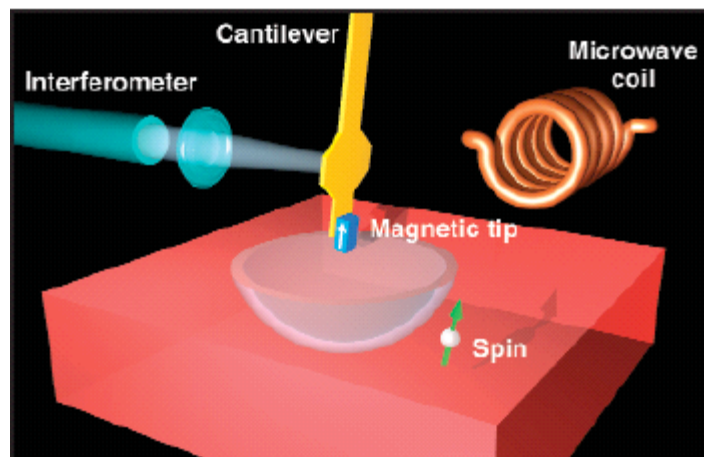


Figure 1: Configuration of the single-spin MRFM experiment.

MRFM is an exceptional tool for studying single-spins because of its inherent ability to couple directly to the electron's magnetic dipole moment. The method can be applied to a diverse set of applications and utilized to the detection of any magnetic moment. This instrument will ultimately allow an end-user to potentially determine 3-D detailed protein structures as well as revolutionize biomolecular imaging.

To optically detect single spins by STM, a small direct-current magnetic field was applied to a sample in an STM system as seen below in Fig 2. A graphite surface (HOPG) with clusters of organic BDPA molecules is placed into an STM system. A magnetic field is applied to the sample, inducing the free radicals in the molecules to precess at the Larmor frequency. Using an STM tip to tunnel into magnetic regions of the sample, a current will flow between the tip and the sample. This current is modulated at the Larmor frequency and the precessing spin activates radio frequency (RF) modulation of the tunnel current. By detecting the RF signal with a spectrum analyser, it is possible to locate single electronic spins on surfaces, detect spin – spin coupling and spin – surface coupling¹³. The researchers found that the proportionality constant (the 'g-factor') between the applied magnetic field and the Larmor frequency was very nearly

equal to 2 — conventional ESR experiments confirm this g -factor for BDPA molecules. The authors also demonstrate that the observed precession frequency scales linearly with applied magnetic field, and disappears over the bare graphite surface.

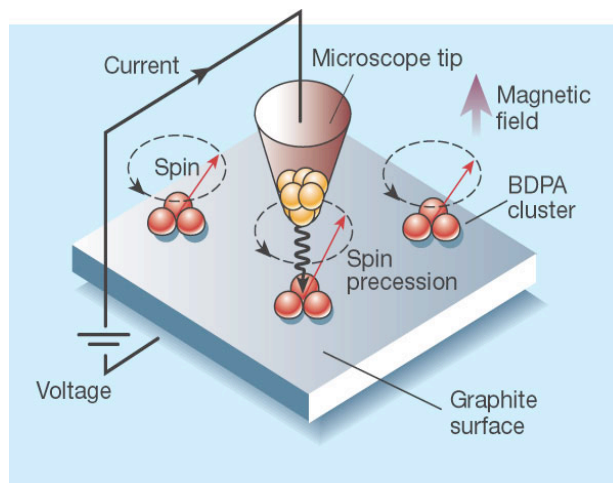


Figure 2: Single-spin optical detection using STM setup.

STM is a natural platform for sensing single spins, as it already provides convenient high resolution imaging of single atoms and molecules. The technique also holds excellent potential for manipulating spins at the single quantum level and lends an excellent platform for quantum computation. Though the physical origin of the spin-sensitive signal is very controversial and several theories have been published to explain the effect, the exciting results suggest that the tool needs further investigation.

Several other techniques have been employed to accomplish optical detection of single spins. The measurement of a single-electron spin was achieved using semiconductor quantum dots⁵ and in a nitrogen-vacancy (NV) defect center in diamond⁴. Optical detection of single spins remains a unique technique, capable of demonstrating accurate measurements in various systems, and with the excellent promise to produce substantial enhancements in nonvolatile memories and electronic information processing.

ELECTRICAL SENSING TECHNIQUES

Electrical detection of single-spin states has been performed in quantum dots⁷, through the use of silicon field-effect transistors⁸, and using current detection⁹. One detection method utilizes a configuration comprised of a quantum dot (QD) in close proximity to a quantum point contact (QPC) as shown in Fig. 3. In this technique, the spin orientation of a single electron in a QD is measured electrically using spin-to-charge conversion of a single electron confined in a QD. The QD acts as a box to trap a single electron, and the QPC operates as a charge detector to determine whether the dot contains an electron or not. Voltages applied to the lettered electrodes define a QD next to a QPC, which is sensitive to the charge state of the QD. By measuring the current through the QPC channel, changes in the quantum dot charge that result from electrons tunneling between the dot and reservoir are measured. The charge on the quantum dot remains constant if the electron spin is up, whereas an electron with down spin can escape and change the charge on the quantum dot. When one electron with unknown spin is injected into the dot, its spin can then be quantified.

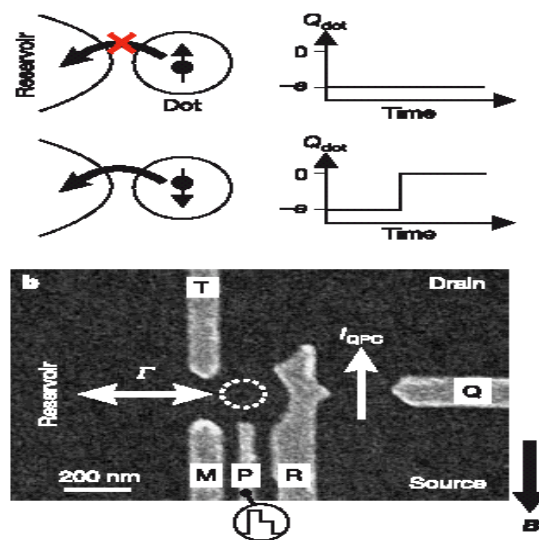


Figure 3: Principle of single-spin detection in quantum dot.

Another electrical single-spin sensing method relies on the use of magnetic resonance to measure spin-flips of a single electron paramagnetic spin center, formed by a defect in the gate oxide of a silicon FET. The measured spin orientation of the electron is then converted to electric charge, which is measured as a change in the source/drain channel current. Fig. 4 illustrates the test apparatus for this technique, which is a single paramagnetic trap, situated in a standard n-channel Si FET. This system is adjusted so that the Fermi level lies between the upper and lower Zeeman levels and if the lower Zeeman level is occupied, it is not allowed to accept any additional electrons from the Fermi level. If only the upper Zeeman level is occupied, then an additional electron can be transferred from the Fermi sea to the lower Zeeman level. If the spin of the electron flips under electron spin resonance, the lower Zeeman level can become filled and produce a doubly occupied trap. This permits the FET to identify between two trapped electron charges versus one trapped charge and convert the spin-flip measurement to an electric charge.

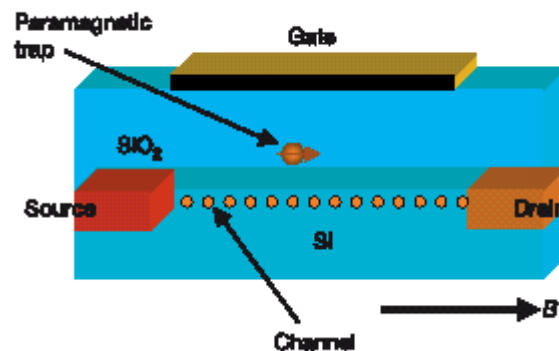


Figure 4: Mechanism for spin-to-charge conversion in FET.

The ability to control spins electrically offers several advantages. In particular, devices could be self-contained on a chip without the need for lasers and optical tables, and electrical implementations could interface naturally with conventional electronic circuits. The QD & FET

detection scheme are unique spin-filtering approaches and may help further our understanding of spins in semiconductors for possible uses in quantum computation. Additionally, the advances in electrical detection of single spins could help facilitate the direct, rather than theoretical, study of the physics of electron spin decoherence, which would be crucial in the further development of manipulating and monitoring the spin of a single electrons for quantum computing.

CONCLUSIONS

The growing interest in the ability to detect and manipulate individual spins eventually promises to yield the creation of next-generation devices such as quantum computers and nonvolatile memories. This paper has provided a broad review of state-of-the-art techniques to detect individual spins using various systems and some potential applications of each approach.

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