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CVD diamond for spintronics ☆

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ABSTRACT

The ability to minimise, control and manipulate defects in CVD diamond has grown rapidly over the last ten years. The application which best illustrates this is probably that of quantum information processing (QIP) or 'diamond spintronics'. QIP is a rapidly growing area of research, covering diverse activities from computing and code breaking to encrypted communication. All these applications need 'quantum bits' or qubits where the quantum information can be maintained and controlled. Controlled defects in an otherwise high perfection diamond lattice are rapidly becoming a leading contender for qubits, and offer many advantages over alternative solutions. The most promising defect is the NV^- defect whose unique properties allow the state of its electron spin to be optically written to and read from. Substantial developments in the synthesis of CVD diamond have produced diamond lattices with a high degree of perfection, such that the electron spin of this centre exhibits very long room temperature decoherence times (T_2) in excess of 1 ms. This paper gives a brief review of the advantages and challenges of using CVD diamond as a qubit host. Lastly the various qubit applications being considered for diamond are discussed, highlighting the current state of development including the recent development of high sensitivity magnetometers.

1. Introduction

Defects in CVD diamond can have a profound effect on certain properties of the diamond, enabling these properties to be tailored to the specific needs of important applications. Properties sensitive to defects include optical properties such as absorption and birefringence [1,2], thermal properties such as thermal conductivity [3], and electronic properties such as carrier mobility and lifetime [4,5].

During the past few years researchers have gained control over quantum behaviour in the solid state at the level of a single spin. What was considered as a "thought experiment" a decade ago is now a reality: spins of single atoms and electrons associated with defects in diamond can be isolated, initialised, manipulated and read using optical techniques [6–8]. Diamond, due to its unique capacity to operate spin devices at room temperature offers the possibilities to create functional quantum devices for applications from nano-scale magnetic imaging to quantum computing. These abilities now enable pioneering investigations of the exploitation of fundamental quantum physics for a disruptive technology, namely diamond spintronics.

These breakthroughs have been based on the negatively charged nitrogen-vacancy (NV^-) colour centre in diamond. This paper will review the properties of diamond that underlie this work, and focus on the progress made in growing synthetic quantum purity diamond using chemical vapour deposition (CVD) with a specific emphasis on the control of point defects and isotopic composition in the diamond. These synthesis developments have lead to decoherence times of the NV^- electronic spin at room temperature of 0.6 ms in polycrystalline diamond as shown in this letter, and in excess of 1 ms in isotopically engineered single crystal samples [9]. In terms of controlling and manipulating defects, diamond spintronics is probably the most demanding of all applications. As such, it is also a key driver for improving defect control, and offers unique ways to characterise defects in diamond with very high sensitivity.

2. Why use diamond as a qubit host lattice?

In the early 1980s the potential power of quantum based computation using qubits was realised and quantum algorithms (such as Shor's factorising algorithm and Grover's search algorithm) were developed. This started the race to find quantum bits or qubits that could be controlled and engineered for quantum information processing (QIP).

Currently the range of qubits varies from non-solid state systems such as photons [10] or ion traps [11–13] to solid state systems such as quantum dots [14], superconductors [15,16] or defects in solid state materials [17–19]. An excellent review of these options and their potential for use in quantum computing is given by [20]. Obviously, if

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a suitable qubit can be generated in a stable, solid state source, this may have practical advantages over other candidates.

To be useful as a qubit, the encoded information must be retained in a quantum, rather than classical, sense for long enough for the quantum operations to be performed. For spin qubits, this retention time for their quantum state can be quantified by the transverse relaxation time, T_2. This is also known as the dephasing or, as will be used here, decoherence time.

There are two main reasons that defects in diamond form good qubits:

(i) Single defect centres can be addressed using conventional optical techniques
(ii) Defect centres can have long decoherence times at ambient temperatures.

These properties start to fulfil the DiVincenzo criteria [21]: they have the possibility to form a scalable physical system, can be written to and read from [22] and have demonstrated CNOT gates [23]. Depending on the defect being studied, the long decoherence time can be significantly longer than the gate operation time, and some defects can be initialised to form a known qubit state.

Other important results demonstrated in diamond are: a 3-qubit system, with brokering (information transfer) to longer-lived nuclear spins (in this case, a nearby ^{13}C), again at room temperature [24], and defects that can be used as single photon sources [25–27].

2.1. Diamond as a low spin lattice

Diamond offers intrinsic properties which limit the impact of spin decoherence mechanisms. These are the mechanisms through which the quantum information encoded to a specific spin is lost — interaction of that spin with its spin environment.

The main decoherence mechanism is spectral diffusion: the existence of other fluctuating spins which, through dipolar coupling to the spin qubits leads to decoherence. While the presence of electronic spins can be controlled by the purity of the material, i.e. minimising the number of intrinsic and extrinsic defect centres which have a non-zero spin, the nuclear spins are controlled by the material choice. For example, none of the three stable isotopes for GaAs is spin zero (^{69}Ga, ^{71}Ga, and ^{75}As). In diamond the major nuclear component, spin zero ^{12}C, is 98.9% naturally abundant, which gives it a significant advantage over quantum dots. The ability to grow diamonds containing only spin-free ^{12}C isotope will potentially lead to possibility of extending coherence time to ultimate limit defined by spin lattice relaxation time. However, the spin lattice relaxation time in diamond is particularly long (reaching ms for ultrapure IIa type material) [9,28].

2.2. Spin defects in diamond — the NV^- defect

Diamond colour centres have been well studied, with over five hundred characterised [29,30]. There are several diamond colour centres that have shown potential for spintronic applications including the nitrogen vacancy defect [31], the nickel–nitrogen NE8 defect [32,33] and the silicon vacancy defect [34].

The most studied diamond defect to date is the NV^- centre, shown with its associated electronic structure in Fig. 1. Its neutral state emits with a zero phonon line (ZPL) at 575 nm and has not so far been viable for spin studies. In its negative state, the nitrogen vacancy defect's electron wave function is made up of six electrons that results in an electron paramagnetic $S=1$ electron spin ground state that has a splitting of 2.88 GHz in the absence of a magnetic field. The optical transition between the spin triplet states ^3E and ^3A possesses a ZPL at 637 nm.

The electronic structure of the NV^- centre means that optical illumination generates a non-Boltzmann spin alignment of the electron spin in the ^3A ground state [35]. The precise reason for this spin polarisation is hotly debated, but is often described to be due to intersystem crossing with an intermediate singlet state: the ^3E $m_s=0$ decays radiatively with conserved spin to the ground state, while the ^3E $m_s=\pm1$ decays via the ^1A singlet state. This is non-radiative, and non-spin conserving, also ending up in the ground state $m_s=0$. Illumination with any light with a shorter wavelength than the ZPL therefore acts as an initialisation step, creating a $|0>$qubit in the ground state, with an effective micro-Kelvin electronic spin temperature even though the crystal is at room temperature.

The initialised qubit can then be manipulated by application of an appropriate length of a resonant RF pulse. Readout of the qubit typically uses confocal microscopy. NV^- defects have a large dipole moment and therefore single defects can be readily addressed [36]. The final state of the ground state qubit is inferred from the intensity of the emitted light following further excitation — $|1>$results in a low fluorescence intensity, because of the comparatively slow, non-radiative singlet decay, while $|0>$produces a high intensity, being a simple radiative transition which is rapidly re-excited, giving further emission.

These properties and successes in manipulating defects have put diamond in the frame as an important QIP material.

3. Methods

3.1. CVD diamond synthesis

Processes that require quantum control in the solid state generally place high demands on the material quality. The quality factors in a crystalline material can be intrinsic defects such as dislocations,

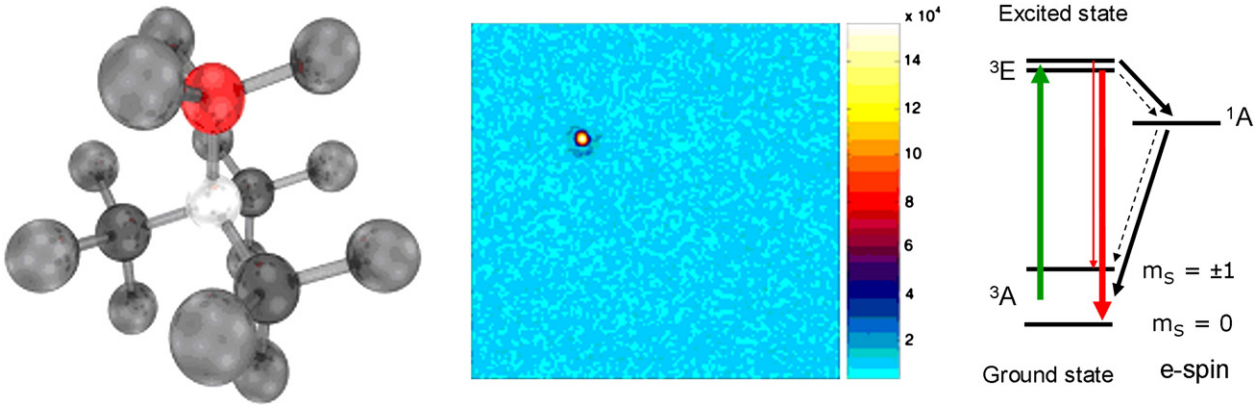

Fig. 1. Left: Nitrogen-vacancy defect in diamond and fluorescence microscopy image of high purity CVD diamond containing single nitrogen-vacancy defect. Right: Energy level scheme of the nitrogen-vacancy (NV^-) defect in diamond showing non-radiative decay from the ^3E $m_s=\pm1$ excited state.