

Introduction

Quantum mechanics was first developed at the beginning of the 20th century as an answer to . In the second half of the 20th century, technological development based on the new understanding of light and matter have led to what was retroactively called the first quantum revolution [1]. Technological developments in the 50s and 60s include the semiconductor transistor, the laser, and nuclear magnetic resonance which have since revolutionized the fields of information science, global communications and medical imaging.

A new field of quantum technology has emerged in the last two decades. This “second quantum revolution” differs from the first one in the usage of individual quantum systems, such as single photons, atoms or electrons [2], which have properties that can not be emulated by larger classical systems. These properties include quantum entanglement, superposition or measurement and form the basis of the newly formed quantum information science [3–5].

Central to quantum information science is the idea of quantum bits or qubits [6], which are the building blocks of quantum information in analogy to the bits of classical information theory. Physical implementation of a qubit could be any quantum system with two well defined quantum states, as long as these states can be initialized, manipulated and readout [7]. Popular qubit candidates include superconducting circuits [8, 9], photons [10, 11], quantum dots [12, 13], trapped ions [14, 15] and single crystal defects [16–18].

Defects in large band gap crystals are sometimes referred to as artificial atoms [19], as the localized wave function of the electrons surrounding the impurity give rise to discrete energy levels similar to that of an atom. Of all the possible crystals and defects, the most studied defect for quantum applications is the negatively charged nitrogen-vacancy center in diamond [20, 21], often abbreviated to “NV center”. Although this particular defect of diamond had been known and correctly identified almost 50 years ago [22], interest in the NV center really sparked after it was first isolated in 1997 [23]. The detection of single NV centers proved that NV centers fluoresce brightly [23], are photostable [24], and that their electronic spin can be polarized and readout optically [25], making them an promising solid state qubit.

Since then, single NV centers have been successfully used to create quan-

tum entanglement over several km [26], to store quantum information at room temperature for more than one second [27], to detect single proteins via nuclear magnetic resonance [28], and for many other applications in quantum communication [29], quantum computing [21] or quantum sensing [30].

As the interest in single NV center grew, diamond synthesis improved significantly [31–33] which benefited not only single NV centers but also NV center ensemble. While single NV center are required for most quantum information processing [34], several other applications benefit from a greater concentration of defects and are therefore more suited to operate with NV centers ensemble. Four of these applications are pictured in Fig. [image bio : mohan2010vivo]

The first application for NV center ensemble is the use of nano or micro diamonds as fluorescent biomarkers [35, 36]. NV centers are good candidates for biomarkers as they emit a bright and stable photoluminescence, and because diamond nanocrystals present low toxicity [37]. Some applications also use the spin degree of freedom the NV centers, either to perform background free fluorescence microscopy [38] or to monitor the angular motion of the nanodiamonds [39, 40]. For most of these applications, NV ensemble provide a better visibility than single NV centers and are therefore preferred.

The second NV ensemble application is for quantum sensing [30]. NV centers are predominantly used as magnetic field sensors [32, 41], although they can also detect electric fields [42, 43], temperature [44, 45], crystal strain [46, 47] or rotation [48, 49]. Both single and ensemble of NV centers can be used for sensing: single centers offer unmatched spatial resolution [50] down to a few nm [28], while ensemble provide better sensitivities due to the larger number of probes [32, 51].

The third NV ensemble application is nuclear magnetic resonance (NMR) dynamical nuclear polarization [52]. Dynamic nuclear polarization consists in increasing the nuclear polarization of a sample by transferring electron polarization to the nuclei bath [53]. Because the NV electronic spin can be optically polarized at room temperature, micro and nano diamonds containing NV centers are promising candidates as hyperpolarization agents [54]. Dynamic nuclear polarization of nuclear spins inside the diamond lattice was demonstrated with single NV centers [55, 56] and NV ensemble [57–59]. Polarization transfer to nuclear spins outside of the diamond is an ongoing challenge [52, 60], but dense NV ensemble are believed to be necessary to achieve high external polarization [54, 61].

Finally, the fourth NV ensemble application is the recent field of spin mechanics [62]. Similarly to optomechanics [63], the goal of spin mechanics is to couple a quantum system to the mechanical degree of freedom of a macroscopic object. Strong coupling between single NV center spin and external mechanical oscillators has been observed [64, 65], but coupling of the diamond motion with NV centers spin has so far only been achieved with

dense NV ensemble [66–68]. Coupling several NV centers to the same mechanical oscillator could also lead to interesting magnetic phase transitions [69, 70].

Most of the NV ensemble experiments discussed previously work under the assumption that the ensemble is constituted of N independent single NV centers. However, as often in physics, *more is different* [71]. Interaction between the NV center themselves or with their environment can lead to significantly different behavior between ensemble and single spins [72–75].

The work presented in this manuscript focuses on some of the

Bibliography

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