The Nitrogen-Vacancy centre in diamond

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The strong covalent bonds between the carbon atoms in diamond are organized in the face-centred cubic lattice and give rise to the many interesting properties of diamond, such as high thermal conductivity and carrier mobility. Diamond is a wide bandgap semiconductor, with a bandgap of 5.5eV, making it transparent to wavelengths in the range from deep-ultraviolet to infrared[1]. However, due to crystal defects, the so-called colour- or luminescent centres, natural diamond can be found with a variety of different colours. One of these colour centres is the nitrogen-vacancy (NV) centre, consisting of a substitutional nitrogen atom and a lattice vacancy. The NV centres are thermodynamically stable, and can be created by irradiation of N^+ followed by an annealing process, causing diffusion of vacancies which become trapped at the implanted nitrogen ions[2].

Nitrogen, a group V element, has five valence electrons allowing the formation of covalent bonds with the valence electron from the three nearest-neighbour carbon atoms. The two remaining unbound electrons can trap an electron from nearby donors (impurities) in the diamond, resulting in the formation of the charged NV^- centre[3].

When irradiated with green light, the NV^- centres show bright red fluorescence, as can be seen in Fig.1. The characteristic photoluminescence spectrum of the NV^- centre has a width of approximately 120nm in wavelength, with the zero-phonon line (ZPL) located at 637nm[4]. The ZPL corresponds to a purely electronic transition resulting in the emission of a single photon. The emission of single photons, even at room temperature, makes the NV centre particularly interesting in the fields of quantum cryptography and quantum key distribution, where single photons are required for information theoretic security[5].

In diamond, only the non-zero nuclear spin of ^{13}C leads to significant spin decoherence, resulting in the NV centre having a spin coherence time on the order of milliseconds[6 7 8]. The long spin coherence time makes the NV centre particularly interesting as a solid-state qubit[9]. The NV^- has spin S=1. The $|m_s = \pm 1\rangle$ ground state sub-levels forms a Λ-type three level system with the first excited state, where the electronic transitions are spin-conserving, even at room temperature[10]. Using optical pumping, the NV centre can be initialised in one of the sub-levels. The difference in intensity of the

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fluorescence from the two spin states can be used to read out the spin state of the NV centre[11]. The easy optical access to the ground state sub-levels combined with the optical readout make the NV centre a good candidate for various quantum information protocols.

With its long spin coherence time, the nitrogen-vacancy centre offers a robust qubit system with easy optical access[12]. Even at room temperature, the NV centre acts as a stable emitter of single photons. However, although the NV centre sounds like the perfect system, everything is not yet perfect. The broad fluorescence spectra result in only small fractions of the photons from the NV being emitted into the zero-phonon line. Also, most of the photons remain in the bulk diamond on account of total internal reflection at the diamond-air interface. Furthermore, the radiative decay is relatively slow. All these factors severely restrict the flux of ZPL photons.

A crucial point is that the problems limiting the ZPL photon flux can be solved, at least in principle, with optical engineering. An attractive option is to embed the NV centre in an optical microcavity tuned to the ZPL wavelength. Constructive interference is possible provided the separation between the mirrors is equal to half the wavelength of the light and at this specific wavelength, a standing wave results. The net result is a much higher density of states for resonant light and a much lower density of states for non-resonant light. A higher density of states means that the photon decays more rapidly resulting in a shorter lifetime and enhanced ZPL emission. The phenomenon of enhanced emission in a resonator is called the Purcell effect, and the ratio between resonant and the original decay rate is called the Purcell factor[13]. By using piezoelectric crystals, the mirror separation can be tuned in such a way that the ZPL will be at resonance, enhancing the emission of coherent photons along the ZPL. My team has already demonstrated a modest Purcell effect on single NV centres. The next step will be to improve the current Purcell factor, before starting with spin dependent fluorescence. My work has already shown that the weak Raman scattering from diamond can be massively boosted with a resonant microcavity. This Raman signal is interesting in its own right – a Raman laser is a possibility - and it has turned out to be a very useful feature in aligning the microcavity for the NV experiments.

The optical microcavities have the potential to put the NV centres back in the game as one of the hottest candidates for quantum cryptography and quantum computing.

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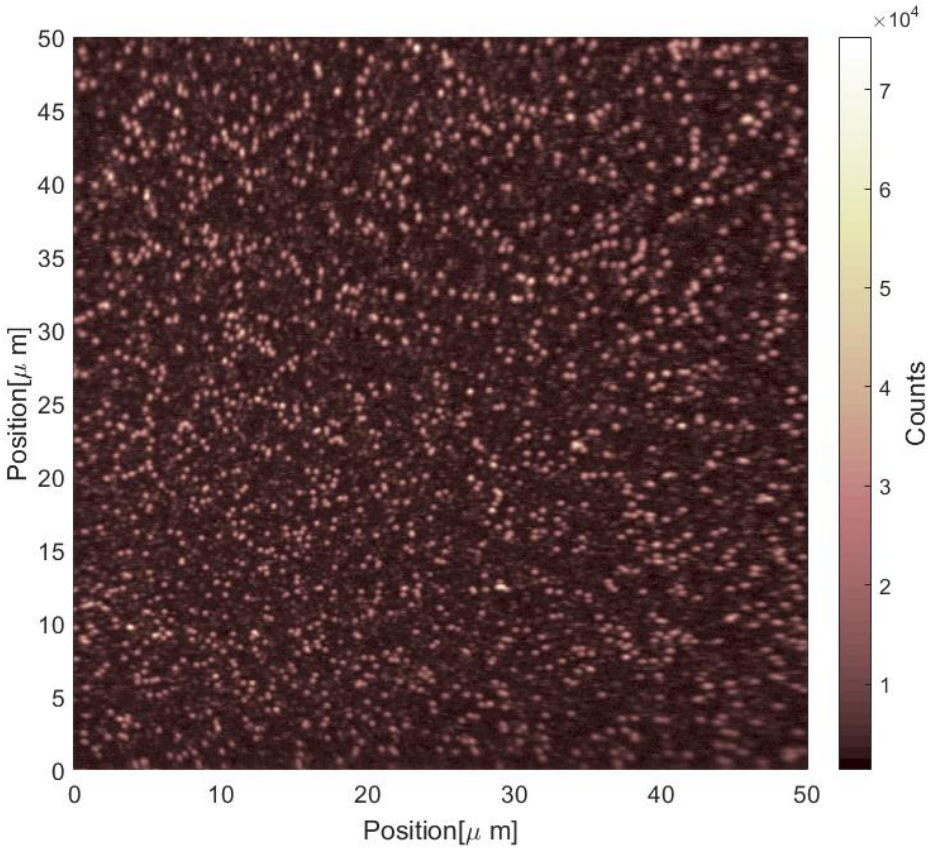

Fig. 1 Photoluminescence scan of diamond. Each of the diffraction limited spots represent a single NV centre.