MATERIALS SCIENCE

Qubits in the pink

Pieter Kok and Brendon W. Lovett

Crystal imperfections known as nitrogen–vacancy defects give some diamonds a characteristic pink colour. Appropriately manipulated, these defects might have rosy prospects as the 'qubits' of a quantum computer.

According to materials scientist F. C. Franck, "crystals are like people; it is only the defects that make them interesting". Ronald Hanson and colleagues would probably agree: writing in *Physical Review Letters*[1], they report new developments in the study of negatively charged 'nitrogen–vacancy defects' in diamond. These systems are rapidly becoming a front-runner for use as the basic unit of quantum information — the 'qubit' — in a solid-state quantum computer.

The lattice of carbon atoms that makes up diamond can contain various substitutional impurities, such as nitrogen or boron atoms. These defects give diamonds their colour, and are often called colour centres. Nitrogen–vacancy (NV) defects give diamond a pink hue, and arise when a nitrogen atom replaces a carbon atom at a position in the diamond lattice next to a vacant site. It might seem unlikely that these two defects should sit right next to each other, but if the diamond is heated, vacancies can diffuse through the lattice until they encounter nitrogen atoms. When this happens, the 'random walk' comes to a halt because the configuration of the two adjacent defects is extremely stable.

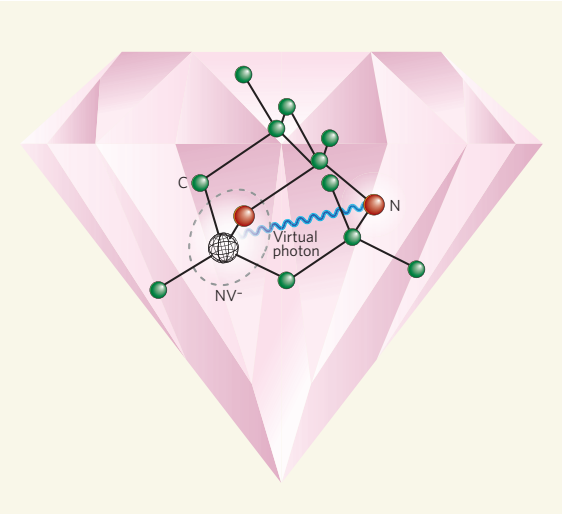

Figure 1 | Defective couple. Hanson and colleagues' experiments[1] look at nitrogen–vacancy (NV^-) defects in the proximity of nitrogen (N) defects in the lattice of carbon atoms that makes up diamond. By tuning the energy of the spin states of the defects using a magnetic field, the defects can be brought into resonance, exchanging energy and polarization via so-called virtual photons. This interaction allows spin control of the nitrogen defect using optical control of the NV^- defect, and the combined system forms a promising two-qubit structure for quantum computing.

NV centres come in two flavours: electrically neutral (NV^0) and negatively charged (NV^-). Here, we are interested only in the NV^- centres, which have an extra electron that is probably donated by another nitrogen defect. The total number of electrons in an NV^- defect that do not form bonds between neighbouring carbon atoms is six, and these electrons have a ground state with total spin $S = 1$. This spin can have three different orientations, described by a magnetic quantum number $m_S = +1, 0$ or -1. If the spin tends to take one of these values, it is said to be polarized.

A well-defined, 'coherent' spin state can be preserved in the NV^- centre for a long time (more than 50 microseconds, even at room temperature[2]). The energy difference between the $m_S = 0$ state and the $m_S = \pm 1$ states is about 12 microelectronvolts. Photons with a microwave frequency of 3 gigahertz have precisely this energy, and can therefore be used to manipulate the spin state of the NV^- centre. To 'read out' the spin state, transitions to much higher energy states are used. These transitions can be induced by shining a laser on the diamond. The light that is emitted when the NV^- centre relaxes back to the lower energy levels tells us what the spin state was. This process is called photoluminescence[3].

The NV^- spins give us much of what we need for a practical qubit — long coherence times and precise external control — and have been widely studied in the context of quantum computing[4]. But considerable obstacles must be overcome before effective quantum computing with NV^- is possible. Perhaps the toughest of these is scaling the system up to many qubits.

Hanson *et al.*[1] take a significant step towards solving this problem. They demonstrate a coupling between an NV^- centre and a substitutional nitrogen centre, N, with no associated vacancy (this is not the same nitrogen defect that supplies the NV^- with its extra electron). This 'N centre' also has a spin, but with different magnetic quantum numbers: $m_S = \pm 1/2$. When a magnetic field is applied, the energy-level structure of both the NV^- and N spins changes, a phenomenon known as the Zeeman effect. At certain values of the field, the energy gaps between the spin levels in the two defects become equal. If there is an interaction between NV^- and N, this 'resonance' allows the two defects to exchange energy and polarization through a so-called virtual photon (Fig. 1). This reduces the photoluminescence signal because the NV^- is no longer in the correct quantum state to emit light. It is this effect that Hanson *et al.* observe[1].

In a further experiment, the authors bring a microwave field into resonance with the NV^- defect. This too leads to an exchange of polarization, this time between the NV^- spin and the field. If the NV^- is isolated in the diamond lattice, a single dip should be observed in the photoluminescence signal. But Hanson *et al.* see two dips in their signal[1], again because of the interaction with the N centre. The two possible orientations of the N spin cause different effective magnetic fields at the NV^- centre, and shift the resonance accordingly. Importantly, this shift allows us to read out the spin state of the N centre by simply observing the photoluminescence of the NV^- centre. The same experiment shows that a specific state of the N centre can be prepared on demand.

As N centres are very common in samples containing NV^- defects, the interactions described above are a main cause of NV^- qubits losing coherence. Being able to control an N centre is a promising way of reducing this decoherence to an acceptable level.

The N–NV^- system can embody two electron-spin qubits, so these experiments represent a significant step towards a larger-scale quantum computer based on the NV^- system. The authors suggest that several NV^- centres could be connected through chains of N defects. This seems to us very ambitious; a better way of achieving a many-qubit register could be to use a form of 'measurement-based' quantum computing[5], in which quantum correlations are created between qubits before any quantum algorithms are executed. In this context, the N–NV^- system could be ideal for a protocol that creates the required quantum correlations between 'broker' qubits through optical manipulations and subsequently transfers them to 'client' qubits that have longer decoherence times, but no optical transitions[6]. With such a strategy, the future for quantum computing would look rosy indeed. ■

Pieter Kok and Brendon W. Lovett are in the Department of Materials, University of Oxford, Parks Road, Oxford OX1 3PH, UK.
e-mail: pieter.kok@materials.oxford.ac.uk

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