QUANTUM COMPUTING

Diamond wedding for spin couple

Observing coherent coupling between two quantum objects in the solid state is hard enough at millikelvin temperatures. Now, this has been achieved at room temperature — using nitrogen defects in diamond — opening up an avenue to practical quantum computing.

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The field of quantum computation is replete with wide-ranging proposals, each looking to marry robustness against decoherence with the ability to couple and measure individual quantum bits (qubits). Although the electron spin associated with a nitrogen vacancy (NV) centre in diamond is a relative newcomer, the results that Torsten Gaebel and co-workers report on page 408 of this issue[1] have thrust it towards the very forefront of candidates for solid-state quantum-information processing. Gaebel *et al.* show that spin-coherence lifetimes for isolated NV centres can be very long, even at room temperature, and go on to generate coherently coupled spin-pairs by implanting N_2 molecules into diamond. Observation of this kind of coupling between single spins at room temperature is without peer, and the fact that the spin measurement has been performed through coupling to optical transitions adds additional power and flexibility to this system.

The NV defect in diamond consists of a substitutional nitrogen atom with an adjacent lattice vacancy. It has an associated electron spin, as well as an optical transition, allowing the measurement of a single defect. Previous studies on NV centres examined diamond with a natural presence of defects, or material that has been bulk electron-irradiated to generate defects throughout the sample[2]. In such systems, the NV spin-coherence time, T_2, is limited by the random distribution of spin defects in the surrounding crystal. Gaebel and colleagues, on the other hand, begin with a clean slate and implant nitrogen ions into otherwise high-purity diamond[3,4]. The defect concentration is kept very low, resulting in a long T_2 of 350 microseconds at room temperature, equivalent to over 10^4 spin-Rabi oscillations (a measure of the amount of coherent manipulation that can be done, in principle, during the 'phase memory time' available). The T_2 time for an isolated NV centre seemed to be limited only by naturally abundant carbon-13 nuclear spins in the diamond, which could be removed in future devices. However, there was a remaining question of what happens when an array of spins is introduced, following an architecture such as that illustrated in Fig. 1a.

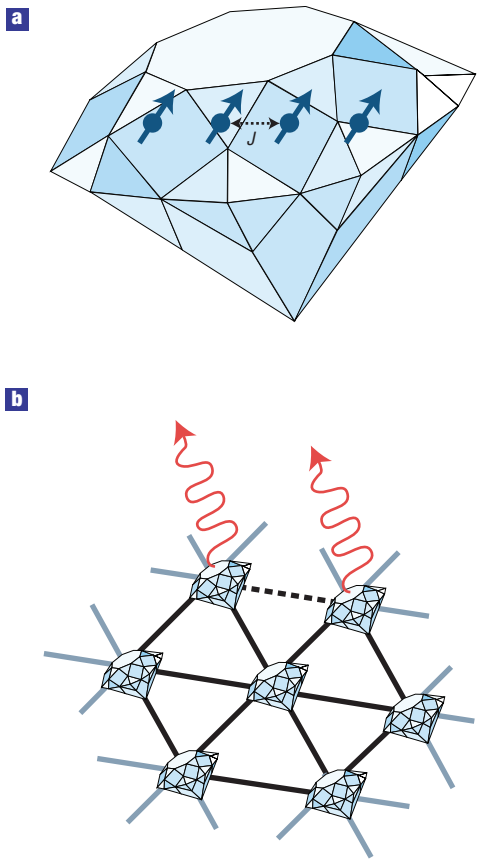

Figure 1 Two antipodal approaches to quantum computing could be achieved with nitrogen defects in diamond, both strengthened by the impressive room-temperature spin-coherence lifetimes and coherent spin–spin coupling presented in ref. 1. **a**, An array of coupled spins within a single crystal carries with it the challenge of controlled implantation. Entanglement between spins is generated via a dipolar coupling, *J*. A scheme for globally controlled quantum computation could be used[11]. **b**, Alternatively, the optical handle on NV centres can be exploited to generate entanglement. In this scheme, each diamond crystal contains one spin qubit acting as a node in a graph. Optical measurements (using lasers) are used both to create entanglement with other nodes, and to drive a computation forward.

Creating an array, or even just a spin pair, by implanting single nitrogen ions lies beyond the current capabilities of ion-beam focusing. The approach of Gaebel *et al.* was to implant N_2 molecules into pristine diamond. The molecule breaks up on its path through the crystal to yield closely spaced pairs of substitutional nitrogen defects, which have an associated electron spin but are 'dark', in the sense of being not accessible by optical measurement. These defects can then be converted into NV centres through annealing, with a conversion efficiency of about 5%. The

abundance of NV–NV pairs is correspondingly low, and instead an NV–N pair was studied.

The NV spin was coherently excited and its evolution observed as a function of time. Coupling between the NV and N spins produces a modulation of the observed signal, whose depth yields a measure of the entanglement, whereas the frequency indicates the coupling strength, in the present case 13 MHz. This may be contrasted with the state-of-the-art demonstration of coherent coupling between spins in semiconductor quantum dots[5] at temperatures of 100 mK, where a tunable exchange coupling with frequency of ~60 MHz was measured between spins with an observed T_2 of ~1 μs. The optically active NV spin does not require such extreme temperatures, and instead can be cooled through optical pumping (while the crystal remains at room temperature). By tuning the magnetic field such that both the N and NV spins are in resonance, the cooling of the NV centre can be efficiently transferred to the N spin.

These experiments show that coupling to light is a powerful tool for initialization and readout at the end of a computation. However, recent ideas have highlighted the enormous power of making measurements on qubits as a way to drive a computation forward[6]. Instead of trying to switch interactions on and off between neighbouring entities in the traditional fashion, measurements on spins are made. Crucially, the system is not measured completely, but rather in such a way as to deliberately not learn about the system fully. Nature itself does not 'know' which of the possible states created the observed outcome. The result is a superposition of the states that could have yielded that measurement. Thus (assuming their coherence lifetimes are long enough), arrays of isolated solid-state qubits can be placed into a highly entangled state (called a graph state) and a computation is then performed by systematically measuring each qubit (see Fig. 1b).

The optical properties and long coherence times of NV spins lend themselves to this kind of graph-state architecture. The observation of spin-pair coupling is also significant, as the presence of more than one qubit at each node can make the construction of the graph more efficient[7]. The dark N spin has even better relaxation properties than the measurable NV centre[8], so together the pair make a good match.

There are several challenges facing the scaling of the powerful properties of NV centres into a full quantum computer. In view of creating an array of spins within a crystal, the N_2 implantation technique will only scale up in a limited way (for example, using N_3^+ or N_5^+ ions). Such defect clusters will be disordered, though this randomness could be exploited as a means to identify each one spectrally[9]. To generate a large and ordered array would require considerable development of ion-beam focusing to obtain exquisite positional control, and the inability to control the conversion of dark N defects into NV centres will also frustrate larger assemblies of coupled spins. However, for graph-state quantum computing with nitrogen defects in diamond using schemes such as those in ref. 6, the challenge will be to develop efficient and coherent techniques for optical readout that do not dephase the spin state, for example, using optical cavities that are fabricated within a single crystal[10].

If, and when, a scalable controlled entanglement is demonstrated, this NV approach will really have won its spurs, and other qubit candidates currently dominating the field may suddenly find themselves outclassed.

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