

SEMICONDUCTOR PHYSICS

Dark spins come to light

The spin of a photoluminescent nitrogen centre in diamond has a long life-time that could be useful as a qubit, for example. It's difficult enough to image such a single spin — imagine using that bright spin to detect nearby invisible 'dark' spins.

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Is there any prospect for solid-state quantum-information technology at room temperature? Most of the semiconductor research aimed at this goal focuses on Si-based or III-V semiconductor-based qubits that offer only low-temperature operation. However, Ryan Epstein and co-workers (on page 94 of this issue)¹ have constructed a microscope and examined single qubits in diamond at room temperature. Moreover, their level anticrossing spectroscopy reveals 'hidden' spins whose spin-lifetimes can be exceedingly long. This provides a fresh tool for scientists trying for a room-temperature quantum repeater, or ultimately, a quantum computer.

Diamond is the extreme case of a semiconductor. Three properties make it the optimal host for room-temperature quantum-information applications². First, its low atomic number leads to very weak spin-orbit coupling. Thus it provides an environment in which the spin is highly decoupled from the lattice. Second, the strong bonding of diamond leads to fewer lattice vibrations. Even at room temperature, the environment it provides is very 'cold'. Third, there is very little nuclear spin to introduce spin decoherence. Even in natural diamond, nuclei with spin, such as ¹³C, are only abundant at the 1% level. Recent advances in chemical-vapour epitaxial growth have provided device-quality material with excellent crystallinity and low defect density.

But finding a good host is only half the battle. Inserting a spin that maintains coherence and easy accessibility represents the next step. The nitrogen vacancy (N-V) centre, which consists of a vacancy in the diamond lattice with a nitrogen impurity substituted in place of carbon in a neighbouring position, is ideal. This defect occurs naturally in some diamonds and can be produced by electron-irradiation followed by annealing. As it is a 'deep' centre, it doesn't provide electrical conductivity in diamond at room temperature. But conductivity isn't necessary for many quantum-information applications. The N-V centre does show the long coherence time essential for quantum information. In addition, its spin has an optical 'handle' that allows

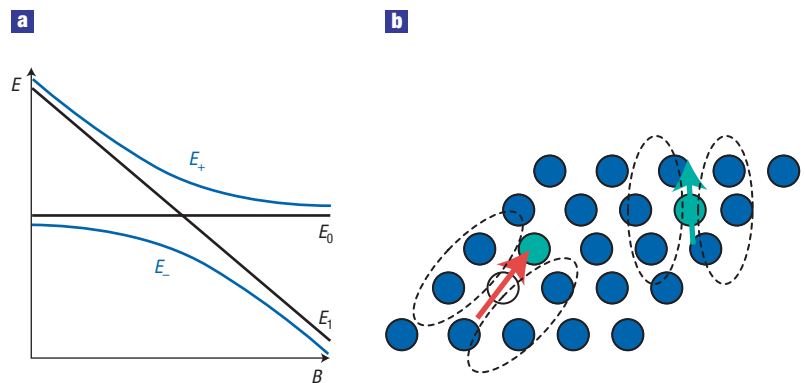


Figure 1 Level anticrossing and spin-spin interaction. **a**, The energy levels E_0 and E_1 cross at a particular value of magnetic field B . A weak interaction connects the two states, forming new states E_+ and E_- that do not cross. Light emission is sensitive to the spin states and reveals the weak interaction. LACs occur for both the ground and optically excited states of the N-V centre. **b**, The spin (red) of the optically active N-V centre interacts with a nearby nitrogen spin (green) through a second, weak dipolar coupling, which 'reveals' the dark spin.

controlled preparation of its spin state. Finally, the light emitted by the N-V centre means the quantum spin state can be read — even for a single centre³.

Epstein *et al.* have built a confocal microscope and magnet that enable them to make use of some simple quantum mechanics in experiments on a single N-V centre. The energy levels for the spin states cross in a magnetic field of about 1,000 G for a particular orientation of the centre. More precisely, the levels would cross in the absence of any additional coupling mechanism between the states (see Fig. 1a), but spin precession and relaxation provide the coupling. Quantum mechanics then leads the states to be repelled in the neighbourhood of the crossing, leading to a level anticrossing (LAC). As the emitted light is sensitive to the spin state, the detected LAC provides the effective spin-relaxation times.

An unexpected LAC near 500 G proved to be even more rewarding. An analysis of the angular dependence revealed the spin spectrum of substitutional, but relatively isolated, nitrogen

impurities. These centres, often labelled as P_1 , are 'dark' — they lack the optical handle of the N–V centres. A few of these centres are near enough to the N–V centre under study to be coupled sufficiently through the magnetic dipole interaction to become visible. The ability to see P_1 centres in small numbers is very valuable because they have been shown to have better room-temperature coherence properties than even the N–V centre. The phase-memory time for P_1 approaches 1 ms in very pure samples⁴.

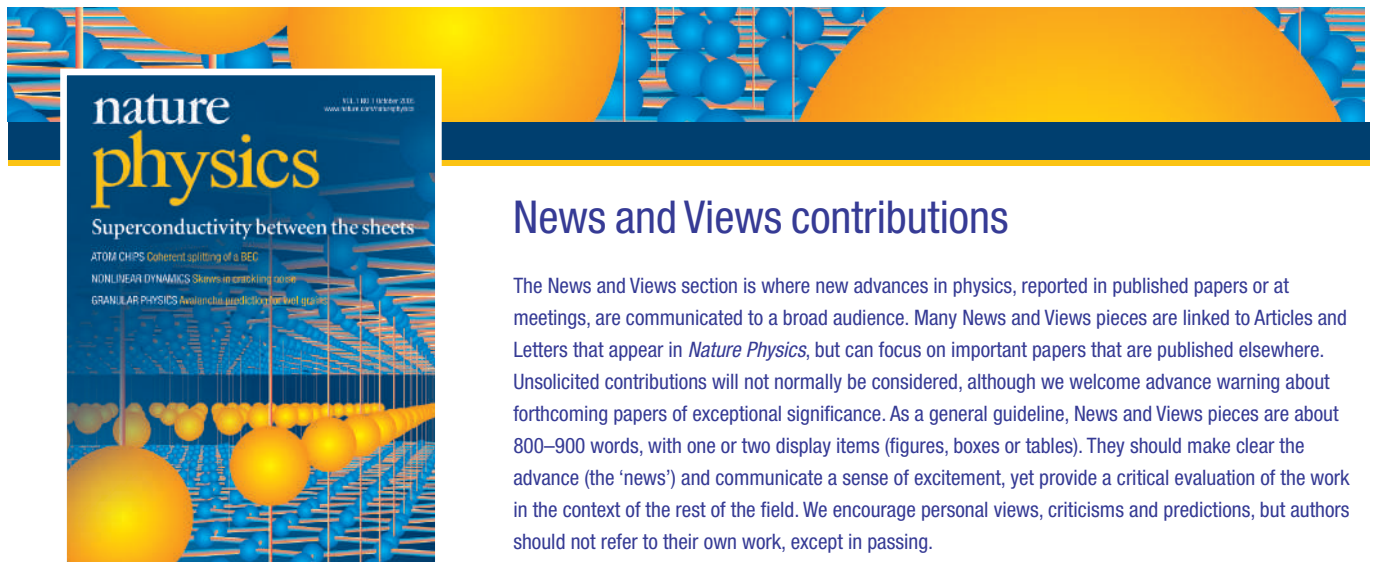
Most designs for quantum computers, such as the Kane proposal⁵, call for qubits with extended wavefunctions that lead to coupling between nearest neighbours in the array through the exchange interaction. For impurity qubits, this implies that the centre is shallow. But shallow centres can be ionized at room temperature, contributing an electron to the conduction band of the host material. Only a low-temperature computer would be possible. From this perspective, N–V and N are deep, lack an extended wavefunction, and cannot be easily scaled up into a

computer arrangement at any temperature. Clearly, a different coupling scheme is required in order to preserve and use diamond's superior properties.

Epstein and co-workers suggest that N–Vs could be coupled through intermediate substitutional nitrogens. They have demonstrated coupling to randomly positioned P_1 centres. The next step requires using the implantation of single N-atoms to form a controlled array. Work in this direction is already in progress in a collaboration between groups at the University of Stuttgart and the Ruhr University of Bochum⁶. These efforts keep alive the hope for room-temperature, solid-state quantum-information technology.

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