not even dreamed of in the early days of electronic structure theory. The work by Stengel *et al.* provides us with a first example of this new philosophy, potentially leading to considerable size reductions in integrated circuits. ❐

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QUANTUM INFORMATION

Mother Nature outgrown

Ultrapure, isotopically engineered diamonds show record spin coherence times. The ideal spin-free material for quantum information processing and magnetometry is one step closer.

Ronald Hanson

The emergence of a new technology is usually preceded by a substantial advance in materials science. For example, the manipulation of single spins in the solid state offers potential applications in quantum information processing, quantum simulations and ultrasensitive magnetometry. But for these applications to become a reality, it is necessary to find materials systems where spins can be controlled for extended periods of time without disturbance. Single-spin control in the solid has been demonstrated in a few materials, but uncontrolled interactions with surrounding spins severely limit the coherence time and therefore the possible implementation of any practical device. On page 383 of this issue, Balasubramanian *et al.* report on the growth of an almost spin-free lattice of diamond, resulting in record coherence times and the narrowest single-spin resonance line ever measured in a solid[1].

Control over the quantum evolution of a single spin was demonstrated in the past few years in defect centres in diamond[2] and in semiconductor quantum dots[3]. In both these systems, the time during which a single spin can be manipulated is limited by interactions with the nuclear spins of the host material. However, in the case of semiconductors from group-IV elements (such as silicon and carbon), isotopes with zero nuclear spin exist. Therefore, through synthesis of isotopically purified material, decoherence from nuclear spins can in principle be fully eliminated, and extremely long spin-coherence times are expected to emerge[4].

For many years, the only diamonds available with a low number of impurity atoms were natural ones, present in the Earth's mantle. With the advent of man-made diamonds, much research effort has been devoted to creating large monolithic crystals of high purity. The first man-made diamonds were grown in the 1950s using the high-temperature–high-pressure method[5]. In these diamonds, the spin dynamics is strongly influenced by electron spins of impurity atoms (noticeably

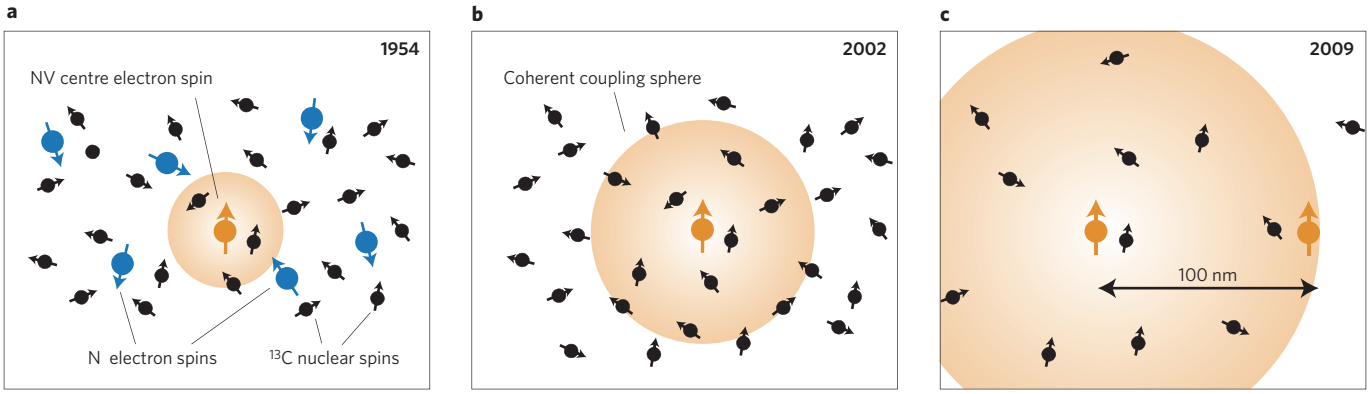

Figure 1 | Engineering spin coherence through materials control. The spin environment of a nitrogen-vacancy (NV) defect centre spin in **a**, typical man-made diamonds grown by the high-temperature–high-pressure method, available since the 1950s (ref. 5), where nitrogen electronic spins dominate; **b**, typical single-crystal high-purity CVD-grown diamond, available since 2002 (ref. 6), where carbon-13 nuclear spins limit the coherence time, and **c**, isotopically engineered ultrapure CVD-grown diamond as reported in this issue[1]. The orange sphere indicates the range over which quantum-coherent coupling to other NV electronic spins is strong enough to prevail over decoherence. With the new material, this range exceeds the optical readout spatial resolution.

nitrogen) as shown schematically in Fig. 1a. For the past few decades, it has been possible to grow diamonds by chemical vapour deposition (CVD), allowing much better control over the number of impurities. In 2002, CVD-grown single-crystal diamonds with an ultra-low level of impurity atoms (<10 parts per billion) were shown to electrically outperform the best naturally occurring diamonds[6]. In these ultrapure diamonds, the effect of electron spins belonging to impurity atoms is completely negligible[7] (see Fig. 1b). The spin coherence times are set by the much weaker coupling to nuclear spins of carbon-13 atoms, which have a natural abundance of 1.1%.

In the ultrapure material, single nitrogen-vacancy (NV) defect centres, consisting of a nitrogen impurity next to a void in the diamond lattice, can be created at precise positions by ion implanting. These NV centres carry an electronic spin that can be initialized, read out and coherently controlled at room temperature. Thanks to these unique properties, NV centres in diamond are a front-runner in solid-state quantum information processing[8,9]. The NV centre's spin coherence time T_2 is typically a few hundred microseconds in ultrapure diamonds with 1.1% carbon-13.

Balasubramanian and co-workers[1] succeeded in synthesizing ultrapure diamond with a concentration of carbon-13 reduced from its natural value down to 0.3%, while maintaining an extremely low number of impurities — 0.05 parts per billion. The reduced number of nuclear spins in the lattice has a striking effect: the electron spin resonance line width, a measure of the strength of the interactions with the nuclear spins, is decreased from 210 kHz to 55 kHz, a record for a single spin in a solid. The spin coherence time is found to increase to 1.8 ms. It is noteworthy that these are room-temperature properties. For both quantum information processing and ultrasensitive magnetometry (Fig. 2) these results could be of crucial importance.

Realization of quantum information processors requires a physical platform that meets stringent requirements. An important figure of merit is the number of operations that can be performed on a quantum bit before an error occurs, which is roughly given by the ratio of the quantum bit's coherence time T_2 to the quantum gate operation time. It is generally assumed that this ratio should exceed 10^4 to be able to efficiently run error-correction protocols. As existing techniques allow spin control on timescales as short as a nanosecond, the newly reported value of T_2 lifts the ratio for NV centre spins to above a million, a new record for solid-state quantum bits and far above the threshold value.

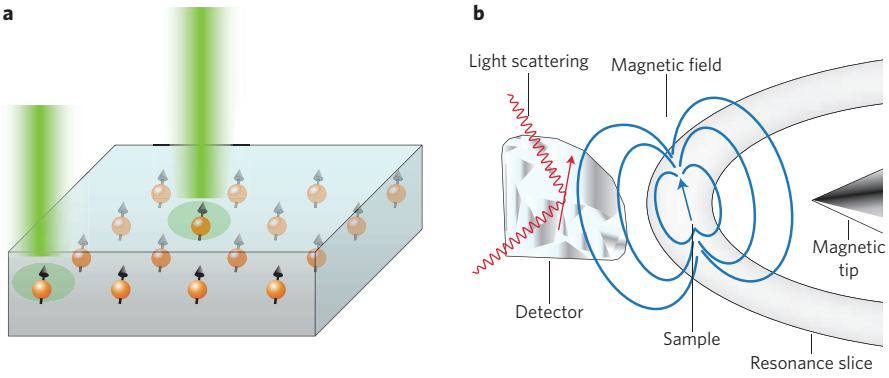

Figure 2 | Possible application of the new ultrapure, isotopically engineered diamond. **a**, An array of coherently coupled spins for quantum information processing and quantum simulations at room temperature. Each spin can be set and read individually using a focused laser beam. **b**, Magnetometry using a single spin in a diamond nanocrystal positioned at the end of a scanning tip. The evolution of the spin state can be sensitive to magnetic fields as small as that of a single proton, allowing for example the identification of the structure of a single molecule. Reprinted with permission from ref. 13. © 2008 NPG.

In a future quantum processor, the individual qubits should be individually addressable, but also be close enough to each other that their coupling is coherent in a quantum sense (the mutual coupling prevails over any of the other interactions present). For spins in diamond, the latter requirement implies that the magnetic dipolar coupling should be stronger than any decoherence. Thus, the longer T_2, the farther the spins can be apart. With the new T_2 values, spins separated by as much as 100 nm would still experience coherent coupling. This separation is large enough for the NV centres to be individually addressed by optical methods[10], and an array of coherently coupled NV centres can now be envisaged.

The NV centre has even more going for it. The combination of its atomic nature, the sensitivity of a single spin and the chemical inertness and non-toxicity of diamond may allow the fabrication of novel devices capable of nanometre-precise microscopy and of probing the atomic structure of single molecules[11,12]. The sensitivity of such devices based on single NV centre spins is proportional to $\sqrt{T_2}$, and is thus limited by the carbon-13 concentration. Balasubramanian *et al.* demonstrate a magnetic sensitivity of 4.3 nT $Hz^{-1/2}$: an improvement by an order of magnitude over the sensitivity measured in diamonds with natural abundance of carbon-13.

The results presented by Balasubramanian *et al.*[1] are just the first step on a new path of materials engineering. Indeed, the latest results from the same collaboration indicate that with 99.99% of carbon-12 in the diamond, the electron spin resonance line width is reduced to a staggering 2 kHz, and T_2 exceeds 10 ms (D. Twitchen *et al.*, unpublished work). The ultimate limit of the spin coherence time will be the spin–lattice relaxation time, which is several seconds for NV centre electron spins at 4 K. These results are also great news for other carbon-based materials such as graphene and carbon nanotubes, in which researchers are aiming for a similar level of spin control. The availability of isotopically purified diamonds again demonstrates that materials scientists have outgrown Mother Nature. ❐

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