Solid qubits

Reliable and consistent technological achievements are required for the development of quantum technologies.

For years, scientific journals have been populated with results demonstrating fundamental advances in the control of qubits and the observation of quantum entanglement in a variety of systems, with the prospects of advanced technologies in communication, information, sensing, and more. Fundamental research will certainly continue, but it has now become essential to improve both materials and algorithms to validate the feasibility of quantum technologies. Indeed, funding agencies in the last couple of years have also placed more emphasis on technological developments, as demonstrated by programmes such as the UK National Quantum Technologies Programme (http://uknqt.epsrc.ac.uk), Dutch Advance Research Centre QuTech (http://qutech.nl) and the development of centres of excellence such as the Centre for Quantum Computation & Communication Technology in Australia (http://www.cqc2t.org).

In the past few years we have published a number of papers reporting technological advances in quantum systems, and two papers included in this issue follow this trend. On page 242, Andrea Morello and colleagues report a demonstration of Bell's inequality violation for a pair of qubits embedded in silicon. Bell's inequality was introduced by physicist John Stewart Bell during the 1960s. A violation of the inequality by a pair of quantum objects placed far apart from one another is a demonstration of the nonlocal nature of quantum entanglement and of the impossibility of describing such entanglement by classical mechanics. Bell's inequality violation has been demonstrated before, so in this sense the work by Morello and co-workers is not conceptually new. What matters, however, is the degree to which the violation occurs. The amount by which the two qubits (represented by the electron spin and the nuclear spin associated with a single phosphorus donor in silicon) violate Bell's inequality is close to the theoretical limit. The results are, therefore, a direct demonstration that quantum entanglement can be created reliably in silicon solid-state devices, which are the basic components of existing technology.

On page 247, Ronald Hanson and colleagues report the improved magnetic sensing properties of the spin of an electron associated with a nitrogen–vacancy (NV) centre in diamond. The electron spin around an NV centre is protected from environmental magnetic noise and can be used to monitor external magnetic fields. But the sensitivity of these measurements depends on the state of the spin before the measurements take place. Hanson and colleagues applied an adaptive protocol, which uses the results of subsequent measurements to initialize the state of the spin in an iterative way. Once again, the sensing properties of NV centres are known, and so are adaptive protocols. But the results show to what extent the sensitivity can be improved and demonstrate the ability of NV centres to measure fast varying magnetic fields, both important technological achievements.

To be clear, these types of result by themselves do not mean that we are ready for the widespread use of quantum technologies. But they are a testimony of the technological achievements that are essential steps for the realization of realistic technologies. As a journal that aims to report both fundamental and technological advances involving matter at the nanoscale, we cannot but applaud these efforts and will continue to follow them with interest. ❐

Controlling an invisible order

Although undetectable by macroscopic magnetic probes, antiferromagnetic order could be used in future spintronic devices.

Spintronics centres on the control of the magnetic properties of matter for memory and logic applications. Efforts in the control of magnetization in ferromagnetic materials and of the spins of moving electrons have led to important achievements from both a fundamental and a technological point of view (see for example our March 2015 focus issue on spin-transfer-torque memory; http://www.nature.com/nnano/focus/stt-mram/index.html). New directions have opened in the last few years, and attention has been given, for example, to skyrmions, a particularly stable configuration of ferromagnetic materials, as well as to magnons, that is, spin waves that can transport information without any movement of electrons. In this issue, on page 231, Tomas Jungwirth and colleagues review progress in another direction in spintronics, namely the control of magnetic order in antiferromagnetic materials.

The idea that an antiferromagnet can be used to store information seems, at first, counterintuitive. Atomic magnetic moments are ordered but their net magnetization is zero, thus invisible to any magnetic probe. In reality, it is not necessary to use magnetic fields to write or read information. Modern spintronics devices rely on the interaction between the spins of moving electrons and local magnetic moments, which is, in principle, possible with antiferromagnets too. Indeed, the advantage with respect to ferromagnetic materials is that once the information is stored, it is more secure as it cannot be easily read, and it is more stable because it is unaffected by spurious magnetic fields, external or internal to the devices.

There are other reasons why antiferromagnets could be useful for spintronics devices. For example many antiferromagnetic materials are insulators, which could be useful for the propagation of spin waves. Also, the intrinsic frequency for the switching of magnetic order is in the terahertz regime, which could lead to very fast responding memory devices.

As Jungwirth and colleagues clearly state in their Review, the field is still in its infancy. It is too early to predict whether devices could be efficient and reliable enough to raise the interest of industry. The recent demonstration of the control of antiferromagnetic order by electrical currents is only the first, though significant, realization of a potentially scalable device (P. Wadley *et al.*, *Science* **351,** 587–590; 2016). But the prospects are numerous and varied, and we can expect rapid and interesting developments in the near future. ❐