QUANTUM INFORMATION

Quantum registers hit the right wavelength

Controlling nuclear spins coupled to an electron spin in silicon carbide has enabled development of a 'quantum register' interfaced with telecom photons, leading to the possibility of distant transport of quantum information.

Siddharth Dhomkar and John J. L. Morton

The control of impurities in optical fibres has enabled the ultralow-loss transmission of near-infrared (NIR) light that underpins our ability to share vast quantities of data around the world. Such optical communication channels are already being upgraded to possess in-built security enshrined by the laws of quantum mechanics, but only over short point-to-point connections. Quantum interfaces that can connect light to matter-based registers of quantum bits (used to generate and purify quantum entanglement among distant sites) are required to allow fundamentally secure optical communication over the long distances required for widespread impact. In this context, carefully selected optical impurities can play a role[1]. Writing in *Nature Materials*, Alexandre Bourassa and colleagues[2] demonstrate exceptional control of a register of electron and nuclear spins associated with the divacancy (VV) defect in silicon carbide (SiC), firmly establishing it as an attractive system for the development of optical quantum networks.

An early quantum interface frontrunner has been based on the nitrogen–vacancy (NV) colour centre in diamond; this atomic defect contains an electron spin, which can interact with a register of nearby nuclear spins in the lattice and has a suitable spin-selective optical transition around 637 nm, enabling coupling to light. Still, the inability of NV centres to emit in the NIR band — where optical fibre transmission is high — combined with the relative immaturity of advanced fabrication in diamond continues to motivate the search for the ideal quantum interface.

Thanks largely to its superior performance in high-power electronics, SiC has seen rapid development with established device fabrication, meeting the exacting standards of the semiconductor industry[3]. SiC accommodates a variety of lattice defects emitting in the NIR spectral region, of which VV is arguably the most promising[4]. The electron spin of the defect acts as the key matter-based degree of freedom, which can represent a quantum bit and couple to an optical transition in the NIR (with emission at around 1,100 nm). In addition to these lattice defects, the host material has trace quantities of nuclear ^{13}C and ^{29}Si isotopes that possess a nuclear spin (Fig. 1), but their presence is a double-edged sword. On the one hand, nuclear spins offer the potential for a versatile quantum register able to store quantum information for long times[5] or perform basic quantum algorithms to increase the fidelity of remotely entangled pairs through a process known as distillation[5]; on the other hand, unintentional electron–nuclear interactions can result in rapid corruption of the quantum information stored in the electron spin, manifested as a reduced spin coherence lifetime. Having two dissimilar nuclear species in SiC assists in partial suppression of such detrimental effects — compared, for example, to materials like diamond or silicon — but is insufficient to completely eradicate them. By tuning nuclear spin concentration, Bourassa and co-workers reveal that a delicate balancing act is indeed achievable to harness power of nearby nuclear spins for well-controlled spin register.

To demonstrate a quantum register in SiC with NIR coupling, Alexandre Bourassa and colleagues begin with a SiC crystal of natural nuclear spin abundance (about 1% ^{13}C and 5% ^{29}Si) and identify a ^{29}Si spin in the vicinity of the VV defect that is strongly coupled to its electron spin. Using a protocol originally devised for NV centres in diamond[6], they transfer the polarization from the electron spin to the

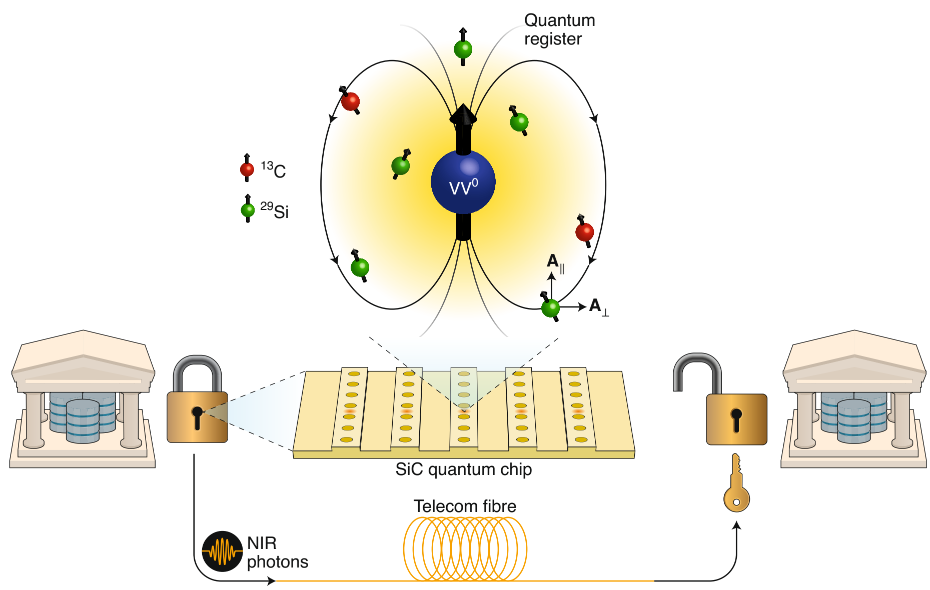

Fig. 1 | Long-distance quantum communication with quantum registers that emit NIR photons. Quantum registers[2] can be created in silicon carbide, each comprising the electron spin of a divacancy impurity (VV^0) that can be entangled with surrounding nuclear spins in the lattice via a hyperfine interaction (**A**). Such registers can process and purify quantum information at the nodes of the network, while emission of NIR photons by the VV^0 defects allows efficient quantum information transmission between the nodes via conventional telecom fibres, bringing us closer to the possibility of virtually unhackable 'quantum-encrypted' data sharing.

nuclear spin to achieve a high degree of nuclear polarization. After initializing both spins in the register, they then apply a series of resonant radiofrequency excitations to entangle both spins (Fig. 1), exploiting a control sequence previously tested using ensembles of SiC defects[7].

Although quantum registers possessing strong electron–nuclear couplings are beneficial for tasks that require fast quantum operations, stronger communication between the spins results in an unintended back-action on one spin as a by-product of an operation being performed on another. Hence, the authors study also single VV spins in isotopically engineered SiC with reduced nuclear spin content. Isotope engineering allows precise coupling to more distant nuclear spins that interact weakly with the colour centre while also enabling long electron spin lifetimes, up to about 15 ms. These results show that tuning the nuclear spin concentration is a practical way to obtain quantum registers with coupling strengths and coherence times that can be optimized for different applications. Moreover, building on the prior knowledge on initialization and readout of the electron spins by means of resonant excitation[4], Bourassa and co-workers corroborate that quantum operations can definitely be performed with minimal error rates, attaining quantum information processing with gate fidelities over 99.98% within the register.

Beyond doubt, these results establish VVs in SiC as a practically viable material platform for quantum technologies and particularly as the nodes of a quantum network connected by NIR optical channels. Nevertheless, there are several hurdles to be overcome before such VV-based quantum interfaces become a reality. Entangling distant qubit registers using light is a clear subsequent milestone but this will require addressing the challenge that photon collection efficiency is low, even when using advanced IR detectors. Adding to the difficulty is the fact that only about 7% of the total number of emitted photons are truly indistinguishable[4] due to phonon-induced broadening of the emission spectrum, making entanglement based on photon interference[8] extremely challenging. Low photon counts have also impeded the progress towards 'single-shot' spin readout in SiC, such that measurements require multiple averages. Here, the nuclear spin registers realized by Bourassa and colleagues could be used for quantum non-demolition measurement protocols[9] to enhance readout fidelity. Addressing these challenges is likely to require the use of photonic structures[10,11] tailor-made for NIR and designed to enhance both the emission and collection of light.

In principle SiC can cope well with the nanofabrication and material engineering needed to enhance photon coupling, which implies that the future is bright for VV-based quantum devices. Some impurities, at least, are worth keeping. ❐

Siddharth Dhomkar[1]✉ **and John J. L. Morton**[1,2]✉
[1]*London Centre for Nanotechnology, University College London, London, UK.* [2]*Department of Electronic and Electrical Engineering, University College London, London, UK.*
✉*e-mail: s.dhomkar@ucl.ac.uk; jjl.morton@ucl.ac.uk*

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Competing interests

The authors declare no competing interests.