DIAMOND-BASED QUANTUM TECHNOLOGIES

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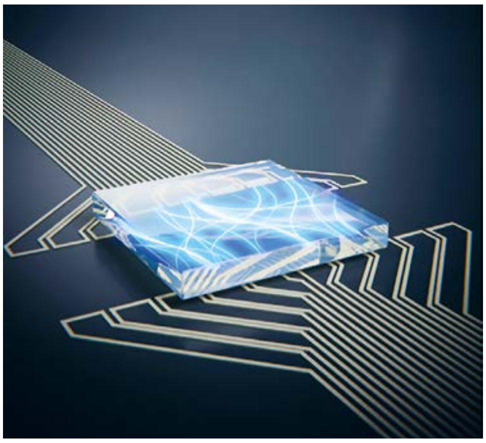
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Optically accessible spins associated with defects in diamond provide a versatile platform for quantum science and technology. These spins combine multiple key characteristics, including long quantum coherence times, operation up to room temperature, and the capability to create long-range entanglement links through photons. These unique properties have propelled spins in diamond to the forefront of quantum sensing, quantum computation and simulation, and quantum networks.

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Over the last decade, the development of quantum technologies such as quantum sensors, computers, simulators and networks has become one of the major goals in science and technology. This envisioned quantum revolution is driven by the potential of quantum systems to outperform their classical counterparts in terms of speed, security, and sensitivity as well as providing functionality beyond what is possible classically. With the launch in 2018 of the Quantum Technologies Flagship (https://qt.eu/), the European Union has made developing quantum technologies a strategic priority. Quantum systems in diamond play an important role in all four pillars of the Flagship - communication, computation, simulation and sensing/metrology [1-4].

Diamond-based quantum technologies revolve around optically active atomic defects in the diamond carbon lattice. The most studied is the nitrogen-vacancy (NV) defect (Fig. 1a), which consists of a substitutional nitrogen atom next to a vacancy (a missing carbon atom). Various other defects such as silicon-vacancy (SiV) and tin-vacancy (SnV) defects are being explored, as well as related systems in materials like silicon carbide, each with their own properties and advantages. The electrons associated with such defects have a magnetic moment called spin, which is sensitive to magnetic fields because of the Zeeman interaction. The quantum mechanical nature of spin enables the creation of quantum superpositions and entanglement. Diamond defect spins offer a unique combination of long coherence times, due to the excellent isolation from their environment by the stiff and pure diamond lattice, and the capability to prepare and measure the spin using optics (Fig 1a). In this article, we discuss the application of spins in diamond for quantum sensing, quantum computation & simulation, and quantum networks.

QUANTUM SENSING

Sensors play a ubiquitous role in our technological society. New capabilities to pick up minute signals in noisy environments is key to opening up new opportunities in fields ranging from medical imaging to nanotechnology. With the drive to develop quantum technologies there is an increasing need for sensors that can probe quantum and biological systems at small length scales. Electronic spins in diamond provide the capabilities to meet this need. The spins are sensitive to temperature, electric fields, and in particular to magnetic fields. Spin-control techniques, similar to those used in MRI scanners and nuclear magnetic resonance, tune their sensitivity from DC to GHz frequencies (Fig. 1b-d). Importantly, these methods work from cryogenic to room temperatures, enabling a diverse range of applications.

In the last decade, magnetometry based on the nitrogen-vacancy (NV) defect in diamond has evolved from demonstrations that focused on its sensitivity and resolution to a microscopy tool that is applied from condensed-matter to biological systems [1-2]. Being particularly suited for probing stray fields close to surfaces, key application areas are magnetism and imaging electrical transport. Because the imaging is magnetic, it enables "looking through" opaque materials such as electrodes on a chip. NV magnetometry has enabled detecting nuclear spins in few-cubic-nanometer volumes and electrical currents in quantum materials such as graphene. A recent application studied by one of us focuses on imaging waves in magnets that transport information with little heat production (Fig. 1 e) [5].

To image a sample's spins and currents, three approaches are common:

1) A diamond with a high-density, thin layer of shallowly implanted NV centers is placed onto a sample (Fig. 1e - top). The simultaneous use of many NV centers yields high imaging speed and sensitivity. Spatial resolution is however limited by the NV-sample distance and the diffraction-limited readout optics.

2) NV-containing diamond nanostructures are deposited onto a sample to achieve nanometer proximity (Fig. 1e - middle). Such nanostructures can also be attached to fibers to realize magnetic endoscopes, or injected into biological samples such as a single cell for in-situ sensing. The temperature-sensitivity of the NV spin can provide insight into a cell's metabolism and transport pathways.

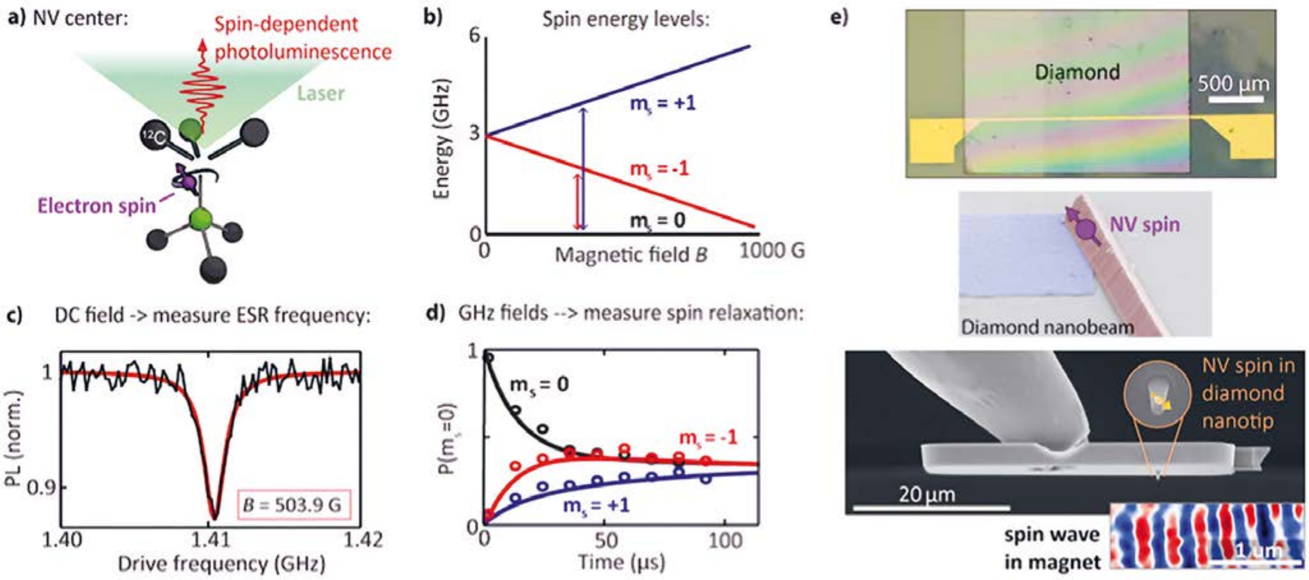
3) An NV in a diamond nanotip is scanned over a sample using an atomic force microscope (Fig. 1e - bottom). While it is a relatively slow technique, it enables a spatial resolution that is only limited by the NV-sample distance (~ 50 nm).

Because of the large application area of high-resolution imaging of magnetic and quantum materials, we anticipate an expanding array of new scientific experiments and an increasingly industrialized use of NV magnetometers.

QUANTUM COMPUTATION AND SIMULATION

Spins in diamond also provide a promising quantum-bit (qubit) platform for quantum information processing [3, 6]. The central elements of diamond-based quantum processors are the optically addressable electron spins of individual defects (Fig. 2). Larger multi-qubit quantum processors are created by coupling these spins together via magnetic-dipole interaction and optical photons (see Fig. 2 and *"quantum networks"*). Additionally, the electron spin can be used to detect, control and measure nuclear and other electron spins in the vicinity, providing more qubits. This network of different types of qubits and connections provides a flexible platform for scalable quantum processors.

Quantum processors with up to 10 fully-connected qubits with coherence times exceeding minutes have been demonstrated [7]. Proof-of-principle quantum algorithms and molecular quantum simulations have been realized. Basic quantum error correction schemes — in which quantum states are encoded in entangled states of multiple qubits so that errors can be detected and corrected — have been realized. Such ●●●



quantum error correction protocols are an essential element of future quantum computers.

Now, the key challenge is to scale up to larger systems. A particularly powerful concept is to realize modular quantum processors, in which many small processors such as the one in Fig. 2 are connected optically (see *"quantum networks"*). Scaling up will require a combination of improved materials and fabrication methods, improved control gates to enable error correction, and chip-scale integration of optical and electronic controls. Such efforts are now underway in worldwide collaborations between universities, research centers and industry.

Figure 1. Magnetic sensing with the nitrogen-vacancy (NV) center in diamond. a) The NV electron spin is an atom-sized magnetic field sensor that is initialized and read out optically. b) NV spin energy levels vs magnetic field. c) Optical detection of the NV electron spin resonance (ESR) frequency yields the DC magnetic field B. d) Relaxation measurement that quantifies magnetic fields at the gigahertz ESR frequencies. e) Top: an NV-diamond placed onto a sample (image originally published in [5]). Middle: a diamond nanobeam with an NV positioned onto a nanostructure (image originally published in [2]). Bottom: A diamond tip that enables spatial imaging with nanometer resolution.

Figure 2. Spin-based quantum processors in diamond. Example showing the different types of qubits and connections available. At the heart of the system are optically active defect centers (shown here : the NV center). The electron spin can be connected to other defect centers over long ranges using photonic channels, as well as over short distances by magnetic coupling (typical 10-50 nm). Additional qubits are provided by nuclear spins, such as carbon-13 isotopes that make up ~1 % of the diamond, and other electron spin defects (shown here : a substitutional nitrogen defect).

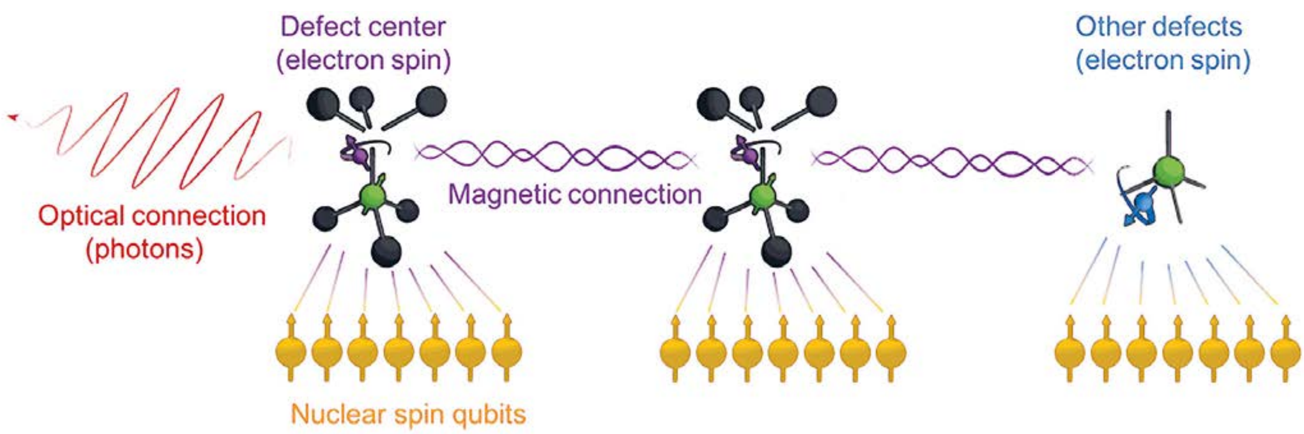


Figure 3. One of the aims of the EU Quantum Flagship program is to realize a pan-European quantum internet. Image credit: SCIXEL and QuTech/TUDelft

QUANTUM NETWORKS

Information networks, of which the internet is a prime example, have revolutionized the way we share and process information. Realizing a quantum internet is a goal of the EU Flagship program (Fig. 3). Such a quantum network aims to exploit the exchange of quantum information for tasks that are fundamentally impossible with current networks. Several such tasks are already known, such as securing communication through the laws of quantum physics, cloud computation with perfect privacy, and secure leader election [4].

In the past two decades, research has focused on establishing the building blocks for quantum networks and proof-of-principle demonstrations of rudimentary quantum network protocols.

The quantum hardware requires two key capabilities:

1) generating entangled links with distant nodes and

2) storage and processing of quantum information in local registers.

While the field of quantum networks had been the exclusive domain of atomic systems in earlier years, solid-state platforms have taken a leading role in more recent years.

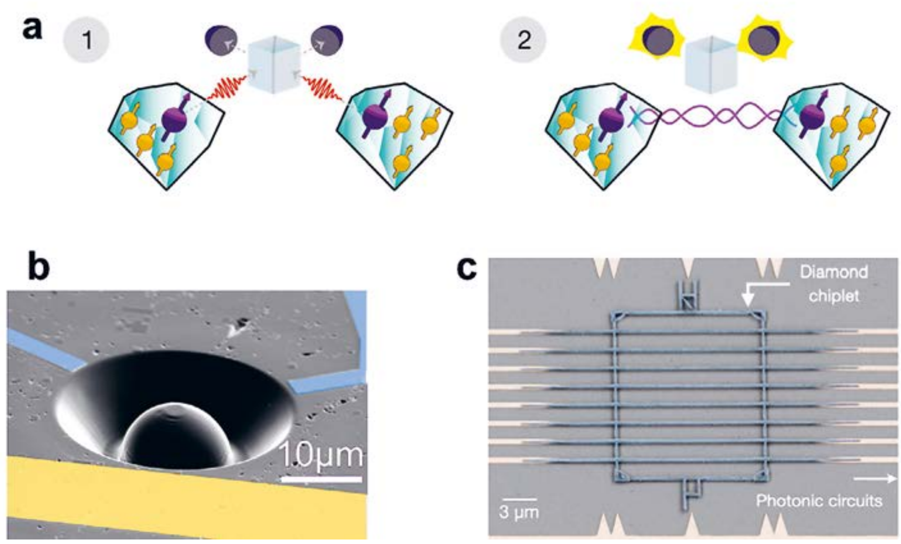


Figure 4. (a) Generating entanglement between remote diamond-based qubits. In step 1, a quantum entangled state between an electron spin and a photonic mode is created, followed in step 2 by single-photon detection behind a beam splitter.
(b) Image of a diamond solid-immersion lens device as used in remote entanglement demonstrations [3]. Image credit QuTech/TUDelft.
(c) Image of an integrated photonics device with a diamond "quantum microchiplet" (blue) containing optical waveguides and defect centers.
Image credit : Noel Wan, MIT [8].

The NV center has been one of the most fruitful platforms, thanks to the combination of well-controlled, long-lived spin states that serve as qubits and a stable optical transition for establishing entanglement with remote nodes (see Fig. 4a for a sketch of the protocol). The first demonstration of entanglement between an NV spin and a photon was reported in 2010. In 2013 two of us reported the first demonstration of entanglement between two separated NV centers using devices as in Fig. 4b. In 2015 we extended the distance between the nodes from a few meters to more than 1 km, and used this setup to measure a violation of Bell's famous inequalities with a minimum of assumptions (often termed loophole-free).

In the past few years research has focused on improving the optical interface and on realizing the first small networks by linking more than two nodes in a single architecture. At the same time, other defect centers, such as the SiV and SnV centers, were found to have promising properties that may enable easier integration into large-scale devices (Fig. 4c) [8].

The near future will see NV centers and similar systems being linked into the first true quantum networks. These networks will still be far from practical for end-users, but they will serve as critical testbeds for development of quantum network protocols, control stack and applications. Research will continue on improving the optical interface by development of cavity systems leading to faster and higher-fidelity entanglement links. Incorporating multiple qubits per network node will enable more functionality. The advances made on quantum computing (see *"Quantum computation and simulation"* above) can often be directly translated to the quantum network nodes.

Besides increasing the number of nodes, their functionality and their performance, large-scale quantum networks also require compatibility of the devices with the existing optical fiber infrastructure. Efficiently converting single photons to match the desired telecom wavelengths is ongoing work. Also, developing a quantum network control stack and interfacing it with the classical networks control is an expanding area of research.

CONCLUSION

Over the last years, spins in diamond have been developed into one of the leading platforms for quantum sensing, computation and simulation, and networks. With several principles demonstrated, a major challenge for the next few years is to realize the broad potential of this platform for basic science and quantum technology. This will bring exciting new opportunities on multiple fronts, from physics to engineering, and from academia to industry.

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