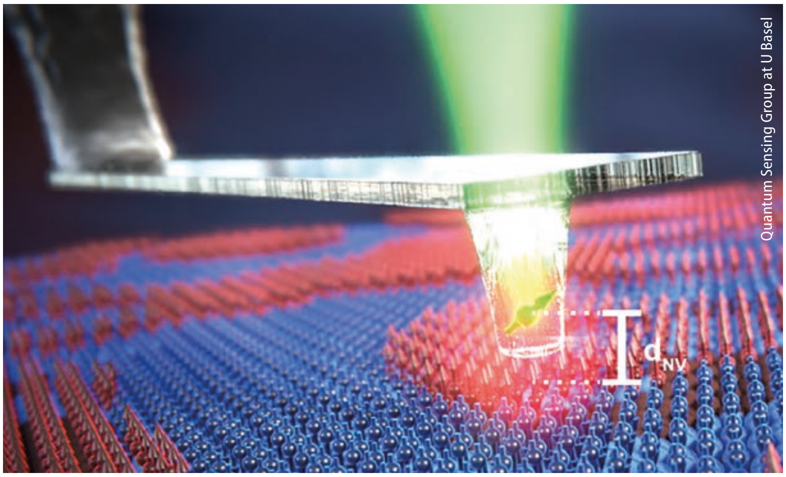
Technology Leaps in Quantum Sensing

Nanomagnetometry advances with customized electronics and fast-switching lasers.

Niklas Waasem, Helmut Fedder, and Patrick Maletinsky

Taking advantage of quantum effects has enabled the first quantum revolution in the 20th century for technologies such as nuclear magnetic resonance spectroscopy, magnetic resonance imaging, and the development of transistors, LEDs, solar panels, and lasers.



Artist rendering of an all-diamond tip containing a single electron spin quantum sensor at its apex. The spin scans at a height of d_{NV} ~20 nm over a sample surface, where d_{NV} defines the ultimate imaging resolution.

Today, amid the second quantum revolution new sensing schemes offer higher sensitivities and better resolution thanks to the possibility to detect and control individual quantum states in microscopic systems like atoms, quantum dots, or color centers. New quantum sensing techniques could lead to applications ranging from quantum gravitometers, precise atomic clocks or low-noise quantum interference microscopy to gyroscopes for self-driving cars or magnetic field sensors in brain-machine coupling.

As quantum sensing technology has matured over recent years, one of the contending techniques for commercially developed systems is based on nanoscale magnetometry with nitrogen vacancy (NV) centers in diamond. These centers act as optically addressable, highly sensitive quantum sensors which are miniaturized and localized to atomic length scales. Employing a scanning-probe approach with one NV center at the tip of an atomic force microscope (AFM) cantilever allows measuring magnetic fields with a spatial resolution on the nanometer scale and an extreme measurement accuracy.

Current solutions rely on the availability of state-of-the art components. Efforts towards commercialization drive improvement of the techniques for capturing or cooling these quantum centers and techniques for initializing, manipulating, and reading out single quantum states. This in turn drives the development of new lasers and electronics as well as miniaturization and innovative ways to allow mass production.

On the nanoscale

Over the last decade, single electron spins in diamond have been established as nanoscale quantum sensors that exhibit excellent sensitivity and nanoscale resolution for imaging and sensing of magnetic fields and other quantities, such as electric fields or temperature [1]. Spins couple naturally to magnetic fields through the Zeeman effect. They can exhibit long quantum coherence times that can be exploited to yield excellent magnetic field sensitivities. Lastly, spins can be localized to atomic length scales that, in turn, enables imaging with nanoscale resolution. These quantum sensors can measure magnetic fields, and thus, electric currents with an unprecedented sensitivity and spatial resolution. Applications include determining magnetic structures on surfaces of multiferroic or antiferromagnetic materials or mapping high-frequency currents flowing in electronic circuits.

Nitrogen vacancy centers in diamond have been recently identified as suitable candidates because the point defect provides an isolated spin state which can be manipulated using microwaves. These combined properties allow for optical detection of magnetic spin resonance (ODMR) at the level of individual NV electronic spins (**Fig. 1**). Magnetometry based on NV center spins measures the energy shifts – or, equivalently, shifts in the quantum-mechanical phase – that a spin experiences in the presence of a magnetic field. These ODMR traces represent the simplest implementation of single-spin magnetometry, where the splitting between the observed ODMR resonances is directly proportional to the magnetic field the NV spin experiences.

To exploit these properties for nanoscale quantum sensing, the NV sensor needs to be brought in close proximity to a sensing target, ideally just a few nanometers. The most flexible approach applies a scanning probe geometry, which scans the NV and sample with respect to each other for imaging. Today, the most robust and sensitive implementation of such scanning NV magnetometry is achieved by using diamond nanopillars that contain individual NV centers at their tip as scanning probes (**Fig. 2**). These diamond tips allow for detection of single electron spins by stray-field imaging at resolutions around 20 nm. This approach, originally conceived in 2012 [2], has since been refined [3] to the extent that commercial solutions are available from companies such as the Swiss startup Qnami AG.

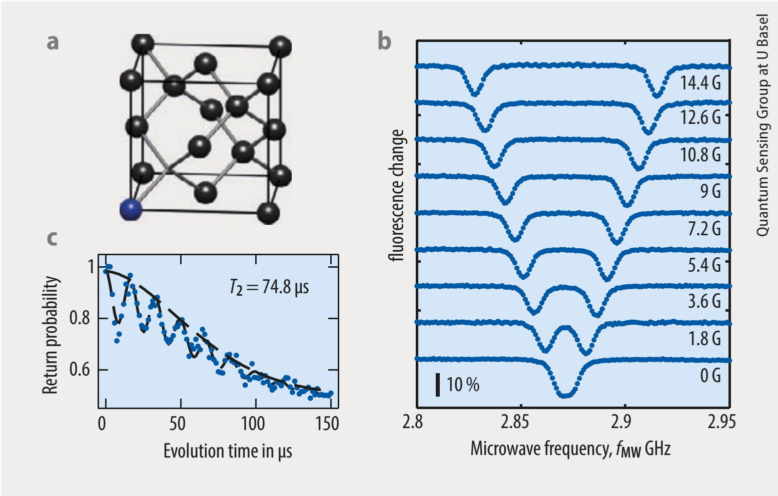


Fig. 1 (a) shows the crystal structure of the NV center. The optically detected electron spin resonance forms the basis for most magnetic field measurements (b). The long NV spin coherence times (decay measurements in c) can be used to improve the magnetic field sensitivity of NVs.

Approaching quantum sensing

A typical quantum sensing experiment starts by initializing the NV center's electron spin with a laser pulse lasting a few microseconds. The laser is typically operating in a wavelength range of 510 – 560 nm which excites the NV center and populates a 'bright' electron spin state that leads to strong fluorescence at around 638 nm when excited. By subsequently applying a microwave pulse, it is possible to flip the spin to a secondary 'darker' state that shows less fluorescence. The spin-state after microwave exposure is read-out with a secondary laser pulse. The spin flip occurs when the microwave frequency matches the energy difference between the two states. As this energy difference depends on the magnetic field around the NV center, it is possible to determine the magnetic field by measuring at what microwave frequency the flipping to the darker state occurs, i.e. when the fluorescence is lowered (**Figs. 1b** and **3**). By applying elaborate sequences of microwave pulses of varying on/off times, it is possible to maximize measurement resolution and to also assess other parameters than the magnetic field, such as electric field strengths and temperature.

This approach requires strong microwave fields at the NV center position, which are achieved by placing a thin wire in its vicinity. Control of the electron spin is implemented with a microwave synthesizer that is switched on and off via a high-isolation switch. The rise and fall times of the switches should last no more than a few nanoseconds – a limit imposed by the typically achievable Rabi frequencies for the atomic transition (which can reach several tens of MHz).

Traditionally, pulse sequences were described as bit strings, where one bit is consumed per sample clock tick. This approach requires a large sample memory and results in long instrument upload times. More recent methods use run length encoding to describe pulse sequences, wherein each pulse is described by an integer number that encodes its duration in clock ticks. For the sparse pulse sequences typical in quantum sensing protocols, this encoding improves upload time and greatly facilitates instrument programming. A typical quantum sensing experiment repeats the measurement sequence many times and the accumulated photon count encodes the probability of the spin state of the final measurement.

Most quantum sensing experiments proceed with a parameter sweep of the interrogation time, which is often equivalent to the interpulse spacing in the sensing sequence [4]. In such cases, one sen-

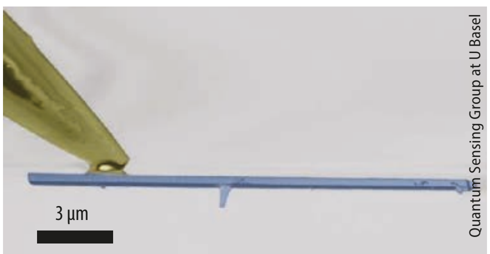


Fig. 2 Scanning electron microscopy image of a real device fabricated at the Quantum Sensing Group in Basel from a high-purity, single-crystal diamond.

sing measurement consists of a set of pulse sequences. Companies such as Swabian Instruments have been able to apply modern single-photon counting approaches to enable fast on-the-fly processing of single-photon detection events in a flexible fashion. Such approaches eliminate common hardware limitations, such as limited histogram range and bin numbers, and greatly facilitate the implementation of novel quantum sensing schemes.

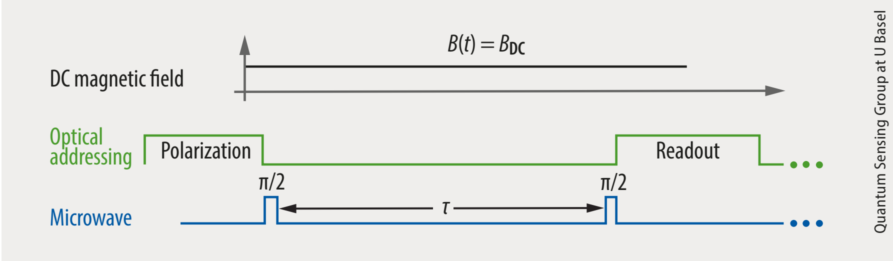


Fig. 3 Typical NV magnetometry sequences using a Ramsey pulse sequence on the NV spin. Optical excitation is used to initialize and measure the NV spin.

Compact fast modulated lasers

The optical initialization and the read-out sequences of the spin state of the NV centers requires precisely tailored light pulses within the excitation spectrum of NV centers. Some quantum-sensing applications also require the ability to generate pulse trains with arbitrary on/off times and excellent intensity stability and repeatability. Until recently, the most common approach to generate such laser pulses involved the combination of a 532 nm continuous-wave laser with a double-path acousto-optical modulator (AOM). However, those setups are difficult to align, bulky, expensive, sensitive to shocks, and require a large or active heatsink. Since 2018, diode lasers, like the Cobolt MLD 515 nm, with direct intensity modulation have offered an alternative solution for use in lab setups and commercial systems.

The main advantages of these diode lasers are their modulation capabilities, such as fast analogue and digital modulation with true off state, as well as precise real-time intensity control without the need for an external modulator. They enable integration of electronics, optics, and a single-mode fiber-coupling into a compact and rugged platform. This allows user-friendly integration with quantum-sensing setups, longer lifetimes without the need for alignment or maintenance, and a more compact footprint.

Outlook

As high-purity diamond quantum sensing cantilevers emerge alongside dedicated control and measurement electronics and high-quality laser sources, the tools for versatile scanning probe quantum sensing experiments are increasingly accessible to a broader audience. Enterprises around the world have also started integrating NV-based ensemble quantum sensors into commercial chip packages, with the goal of realizing the first mass produced products that leverage quantum-enhanced sensing. Further breakthroughs promise to transform quantum-sensing technologies into a versatile range of sensor products.

[1] *M. Chernobrod* et al., J. Appl. Phys. **97**, 014903 (2005)
[2] *P. Maletinsky* et al., Nat. Nanotechnol. **7**, 320 (2012)
[3] *N. Hedrich* et al., Phys. Rev. Applied **14**, 064007 (2020)
[4] Photonics Spectra, bit.ly/3ue5mvQ (2020)

Author

Dr. Niklas Waasem, HÜBNER Photonics GmbH, Wilhelmine-Reichard-Str. 6, 34123 Kassel, +49 561 994060-24, niklas.waasem@hubner-photonics.com, hubner-photonics.com