White paper

HÜBNER Photonics

Technology leaps in quantum sensing

- Advances in nano magnetometry using tailored electronics and fast-switchable lasers

Taking advantage of collective quantum effects has enabled the so-called 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. 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.

Emerging quantum sensing techniques could lead to the improvement of sensing technologies ranging from quantum gravitometers and accurate atomic clocks to low-noise quantum-interference microscopy and ultimately find commercial uses in gyroscopes for self-driving cars, or brain-machine interfacing via magnetic-field sensing.

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 highly miniaturized and localized to atomic length scales. Employing a scanning-probe approach with one NV center at the tip of an AFM (Atomic Force Microscope) cantilever allows measuring magnetic fields with a spatial resolution on the nanometer scale and an extreme measurement accuracy.

Irrespective of which quantum sensing technology prevails, 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. In this white paper we give an overview of the current proposed solutions for quantum sensors based on NV center magnetometry.

Nanoscale quantum magnetometry

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 (GHz) flowing in electronic circuits.

Nitrogen vacancy (NV) 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 (**Figure 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 method of implementation of such single-spin magnetometry, where the splitting between the observed ODMR resonances is directly proportional to the magnetic field the NV spin experiences.

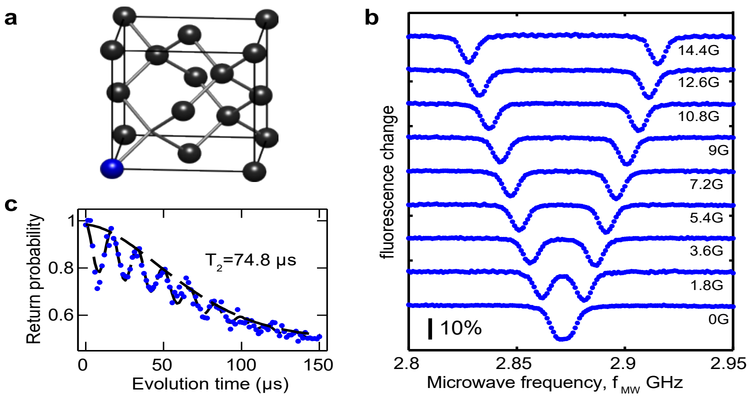

Figure 1. *The basics of NV center spins in diamond. (a) Crystal structure of the NV center. (b) Optically detected electron spin resonance, which forms the basis for most magnetometry applications. (c) Spin-coherence decay measurements. The typically long NV spin coherence times can be exploited to further enhance magnetic-field sensitivities of NVs. Courtesy of the Quantum Sensing Group at Basel University.*

To exploit these attractive 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 (See **Figure 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 today from companies such as Swiss startup Qnami AG.

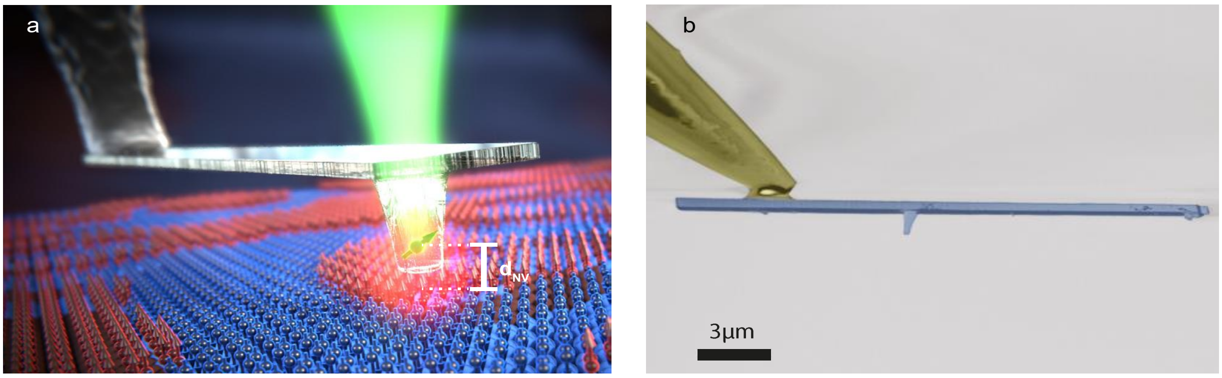

Figure 2. *Nanoscale quantum sensors based on single spins in diamond. (a) Artist rendering of an all-diamond tip containing a single electron spin quantum sensor at its apex. The spin scans at a distance of dNV~20 nm over a sample surface, where dNV defines the ultimate imaging resolution of the approach. (b) Scanning electron microscopy image of a real device fabricated from a high-purity, single-crystal diamond. Courtesy of the Quantum Sensing Group at Basel University.*

New approach to 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 the wavelength range of 510 nm – 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 (see **Figures 1(b) and 3**). By applying elaborate sequences of microwave pulses of different frequencies and varying on/off times, so called "sensing protocols" 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 most efficiently 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).

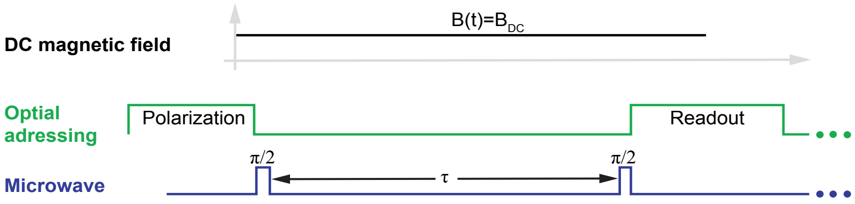

Figure 3: *Typical NV magnetometry sequences using a Ramsey pulse sequence on the NV spin. Optical excitation is used to initialize and measure the NV spin. Courtesy of the Quantum Sensing Group at Basel University.*

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 sensing 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.

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. Other important parameters are listed in the table below:

Wavelength	510 nm – 560 nm
Modulation rise & fall time	<10 ns
On/off extinction ration	>60 dB
Beam profile	Gaussian
Spectral purity	>40 dB
Polarisation extinction ratio	>100:1

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, these laser+AOM setups are difficult to align, bulky, expensive, sensitive to shocks, and require a large or active heatsink. Since 2018, laser diodes at 515 nm with direct intensity modulation have offered an alternative solution for use in lab setups and commercial systems.

The main advantages of these laser diodes 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 also 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. **Figure 4** shows typical modulation characteristics of a 515 nm laser diode with a modulation frequency of 10 kHz.

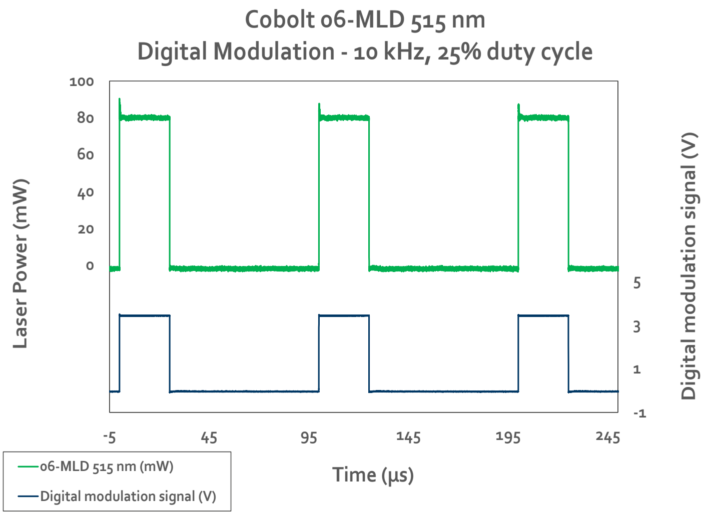

Figure 4: *Output power trace over time of a modulated 515 nm laser diode (Cobolt 06-MLD 515 nm). The modulation characteristics of the 2020 model were optimized for quantum applications. Courtesy of HÜBNER Photonics.*

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.

References

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About the company

HÜBNER Photonics *is committed to supplying high performance and innovative lasers that meet or exceed the market's expectations concerning quality, reliability and robustness. HÜBNER Photonics offers the full range of high performance Cobolt lasers, the CW tunable laser C-WAVE along and a full selection of C-FLEX laser combiners. Through continuous technology development, customer orientation and an ISO certified quality management system, HÜBNER Photonics has become a preferred supplier of lasers to major instrument manufacturers and leading research labs for cutting-edge applications in the areas of fluorescence microscopy, flow cytometry, Raman spectroscopy, metrology, holography, nanophotonics and quantum research. HÜBNER Photonics has manufacturing sites in Kassel, Germany and Stockholm, Sweden with direct sales and service offices in USA and UK.*