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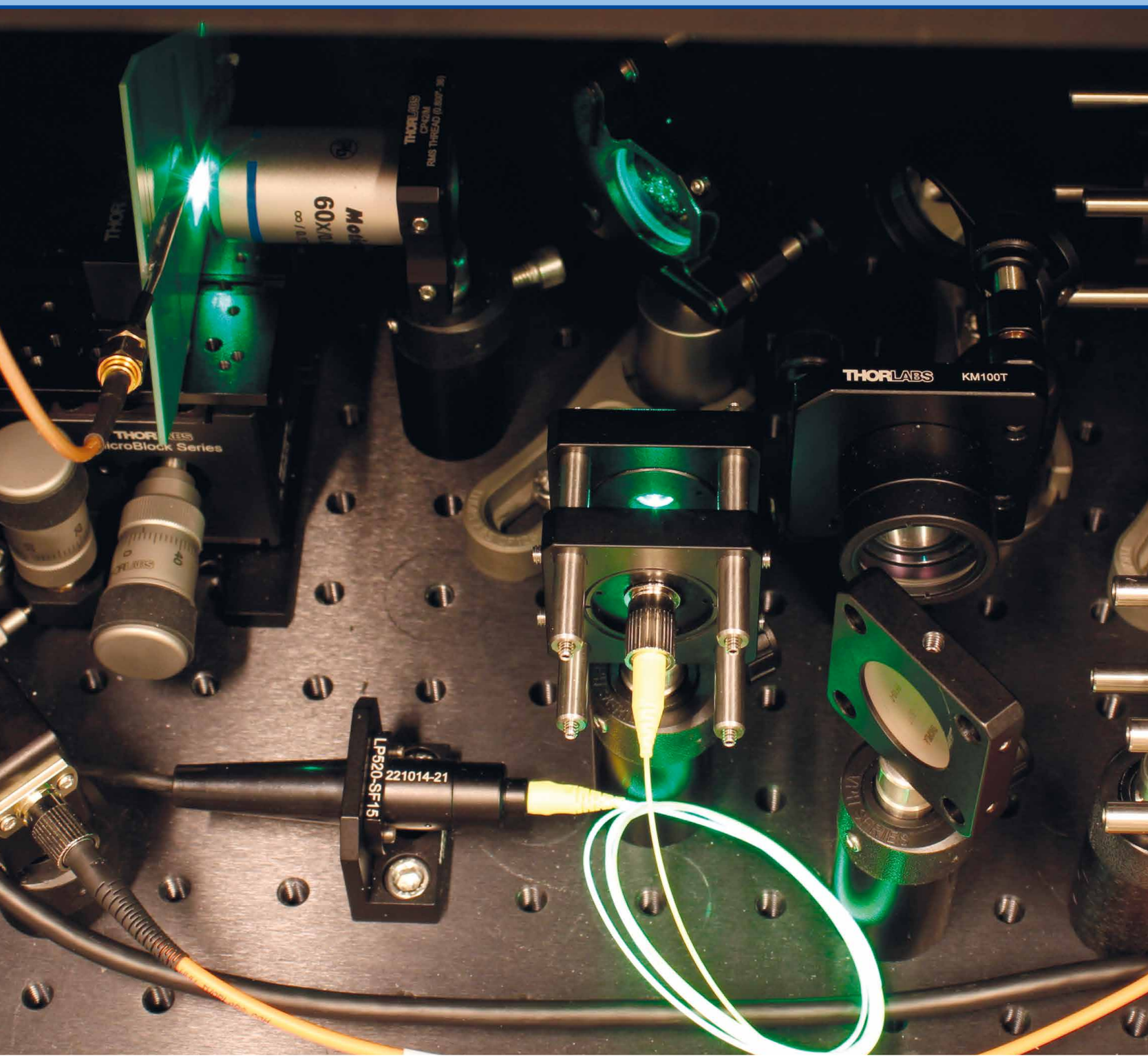

- THEME: QUANTUM TECHNOLOGY
- SCALABLE TESTING OF SUPERCONDUCTING QUANTUM CHIPS BELOW 100 MK
- PRACTICAL ROOM-TEMPERATURE QUANTUM MAGNETOMETERS
- WHAT NOW: STATICALLY INDETERMINATE?
- PRECISION FAIR 2026 PREVIEW

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The cover illustration (featuring a laboratory free-space optically detected magnetic resonance set-up) is courtesy of Tjeerd Bollmann (Saxion). Read the article on page 8 ff.

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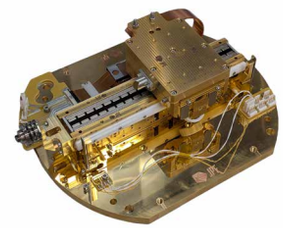

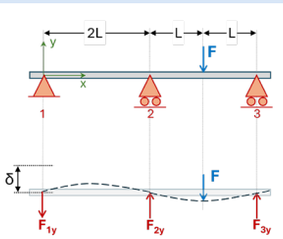

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QUANTUM NEEDS MANUFACTURING AT THE TABLE

When should a manufacturing engineer become involved in developing a quantum system? My answer is: while the design is still open to change. Decisions about interfaces, materials, assembly and testing determine whether a promising experiment can eventually become a reliable product. We should give manufacturing expertise a place much earlier in quantum development.

The Netherlands has a strong foundation to build on. Across Delft, Eindhoven, Leiden, Twente and Amsterdam, researchers and entrepreneurs are developing technologies for quantum computing, communication and sensing. Through QDNL, we have invested as a country in connecting these strengths. We also have an experienced high-tech manufacturing industry, accustomed to translating demanding requirements into working machines. The task now is to bring that manufacturing knowledge into quantum development.

For readers of *Mikroniek*, many of the engineering questions will sound familiar. How do you maintain alignment under changing operating conditions? How do you control vibration, thermal drift and electronic noise? And how do you build a second system that performs as well as the first? The requirements differ between quantum technologies, sometimes considerably. Precision engineering, photonics, electronics and systems integration all have a contribution to make.

Working together will take more than matching a technical need with a supplier. Quantum developers need to explain which specifications are essential to performance and where there is room for engineering choices. Suppliers need enough understanding of the physics to challenge requirements and propose alternatives. Both sides will also need frank conversations about costs, responsibilities and the volumes that can realistically be expected.

The Quantum Manufacturing Alliance (QMA), which Brainport Development will coordinate on behalf of QDNL, will help build these connections. As we prepare to start its activities, our focus is practical: understand the industrialisation challenges of quantum companies, identify relevant Dutch manufacturing expertise and help partners develop concrete collaborations. This is a national programme, connecting Dutch suppliers with quantum technology developers in the Netherlands and internationally.

For high-tech suppliers, a useful first step is to examine where their existing capabilities could meet the requirements of quantum hardware. Which processes can deliver the necessary precision, stability or cleanliness? What has already been demonstrated in other applications, and what would need further testing? The articles in this issue offer a starting point. Read them with your own engineering expertise in mind: you may recognise a problem you have solved before, or one worth investigating.

There is still considerable uncertainty about which quantum technologies will scale fastest, and when demand will grow. As the QMA gets underway, we will help companies explore where there is a basis for working together. We want those connections to lead to joint development projects and commercial relationships in which both sides learn and earn. Manufacturing partners can help shape the design while learning what it will take to supply it. That is a good reason to be at the table early.

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ENGINEERING MOTION BELOW 100 MK, WHERE EVERY MW MATTERS

Quantum processors need more than good qubits. They also need equipment that can test many devices efficiently at their operating temperature. To address this challenge, JPE is developing a cryogenic probe system for wafer-level quantum-chip testing below 100 mK, enabling more scalable and cost-effective characterisation of quantum devices. The system builds on JPE's experience in precision positioning, cryogenic mechatronics and complex system development. The integration with a dilution refrigerator platform is being investigated within a joint R&D effort with Bluefors.

AUTHOR'S NOTE

Jordan Bos works at JPE, located in Maastricht-Airport (NL), at the interface of technical product development, system engineering and business development. JPE provides high-tech project engineering and develops precision positioning and mechatronic solutions for cryogenic, vacuum and quantum-tooling applications.

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JORDAN BOS

Testing in the extreme cold

A classical computer uses bits that are either 0 or 1, while a quantum computer uses qubits. Qubits can perform operations that are not possible with classical bits, but they are also very sensitive. Heat, electromagnetic radiation, magnetic fields, vibration and even the measurement electronics can affect their behaviour. Superconducting qubits therefore operate in a dilution refrigerator, typically around 20 mK. At this temperature, the device is superconducting and thermal noise is low enough for accurate quantum measurements [1,2].

1

Concept of the cryogenic probe system, comprising mK probing modules with an overall envelope of approximately Ø 470 mm × 460 mm, integrated into the lower part of a dilution refrigerator. The system combines in-situ positioning with temporary electrical contact at mK temperature. The rectangular access opening and modular architecture provide a scalable platform for future extensions, such as a cryogenic load-lock for automated wafer handling and loading.

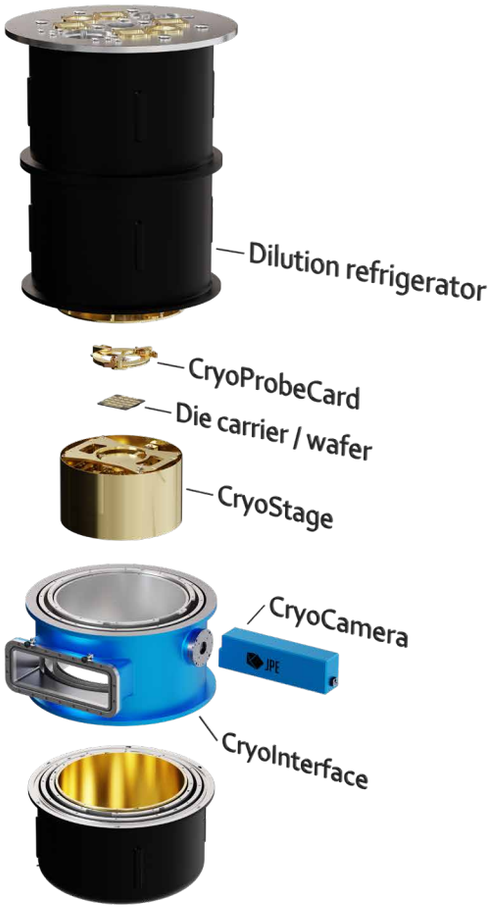
Today's superconducting processors usually contain anywhere from a few dozen to a hundred physical qubits in a size of approximately 20 mm x 20 mm. Google's Willow processor contains 105 qubits and IBM's Eagle contains 127 [3,4]. A useful fault-tolerant quantum computer will require far more. The exact number depends on the architecture and error-correction method, but estimates range from hundreds of thousands to more than one million physical qubits [5,6,7], which requires large-scale infrastructures.

This creates a test and yield problem. The fabrication process may produce individual structures with good yield using the semiconductor infrastructure, yet a larger quantum processor only works well when all qubits, resonators, couplers and interconnects fall within their required range. Room-temperature measurements can screen basic electrical structures, but they cannot show the complete quantum performance. Each superconducting chip, and ultimately each qubit, must therefore be measured and tuned near its operating temperature at the millikelvin (mK) level. Cryogenic testing is not only a final quality check. It is also an important feedback loop for chip design and fabrication.

From packaged chips to cryogenic probing

Today, a superconducting quantum chip is usually diced, wire-bonded and packaged before it is tested at mK temperature. The package provides mechanical support, electrical connections and shielding. The complete assembly is loaded into a dilution refrigerator, cooled down, measured and warmed up again. Depending on the system and measurements, one test cycle can take days. This method is suitable for laboratory research, but it does not scale well. Much of the cycle is overhead rather than measurement time: preparing the chip, connecting it and cooling the complete setup. As the number of devices grows, this overhead becomes a serious bottleneck towards a useful quantum computer.

The semiconductor industry solved a similar problem with wafer probing in ambient environment. A probe station aligns a wafer below a probe card. Electrically conductive



2

Modular breakdown of the architecture into dilution refrigerator, CryoProbeCard, CryoStage moving a wafer or die carrier, CryoCamera and CryoInterface.

probes touch the contact pads of one die, the die is tested and the stage moves to the next die. Devices are tested before packaging, so problems are found early and process information is collected across the wafer.

The same approach is attractive for quantum devices. A cryogenic probe system can test a wafer or a set of unpackaged dies in one cooldown. The stage moves from device to device, while the probe card and measurement infrastructure are reused. This removes repeated packaging from early screening, can increase characterisation throughput by more than a factor of ten (by testing many devices within a single cryogenic cycle and distributing the loading, cooldown and warm-up overhead across them), and shortens the chip-development feedback loop

At first glance, this seems like a straightforward adaptation of existing wafer-probing technology. However, the challenge lies in the extreme operating environment. Superconducting quantum devices must be characterised at mK temperatures, in high vacuum, while maintaining a low-noise environment with minimal thermal, mechanical and electromagnetic disturbances. At 20 mK, only a few tens of microwatts of cooling power are available at the coldest stage of the dilution refrigerator. As a result, every movement, measurement cable, optical component and heat leak becomes part of the engineering problem. Designing an mK probe system therefore becomes as much a challenge in environmental control as in precision positioning.

Cryogenic wafer probers already exist at higher temperatures. Commercial systems operate around 4 K or below 2 K [8,9]. These temperatures are still far above the approximately 20 mK operating point used for many superconducting qubit measurements. Bringing wafer-level probing into the mK regime is therefore not simply a matter of making an existing probe station colder. It requires a fundamentally different balance between cooling power, heat generation, shielding, motion and system integration. This is the technological gap that Bluefors, a leading supplier of dilution refrigerators, and JPE are addressing through a joint R&D effort on mK probing. Figure 1 shows the current concept.

One architecture, five modules

The current development architecture consists of five modules (Figure 2). Bluefors is responsible for the dilution refrigerator platform, while JPE develops four modules that are designed for integration into this dilution refrigerator architecture. Together, the partners are investigating how these modules interact and can be integrated to enable mK probing. The modular approach provides flexibility for different system configurations and supports future scalability towards larger cryogenic platforms and increasing quantum-chip sizes.

The CryoStage moves a wafer or a carrier with multiple dies in X, Y and Rz; a Z motion then brings the devices into contact with the probes. The CryoCamera measures the alignment between the probes and the contact pads. The CryoProbeCard contains the temporary electrical contacts and helps create a controlled environment around the quantum device. The CryoInterface connects the JPE modules and the loading path to the dilution refrigerator [10,11]. This split makes the development manageable, but it does not make the modules independent. The stage affects heat input and vibration. The camera needs optical access, but light can heat or disturb the device. The probe card must combine accurate contact, signal quality, shielding and thermalisation. All modules compete for limited space inside the dilution refrigerator.

This is where complex system development becomes important. JPE translates the measurement needs into system and module requirements, defines the interfaces and checks the complete performance chain. A local improvement is only useful when it does not create a new problem elsewhere. For example, a stiffer connection can improve motion performance but also increase the heat path to the cold stage. The modular architecture also supports step-by-step validation. A module can first be tested separately and later in a more representative assembly. This reduces design risk, simplifies system integration and allows the design to change as quantum-device requirements develop.

The CryoStage: motion without continuous heat

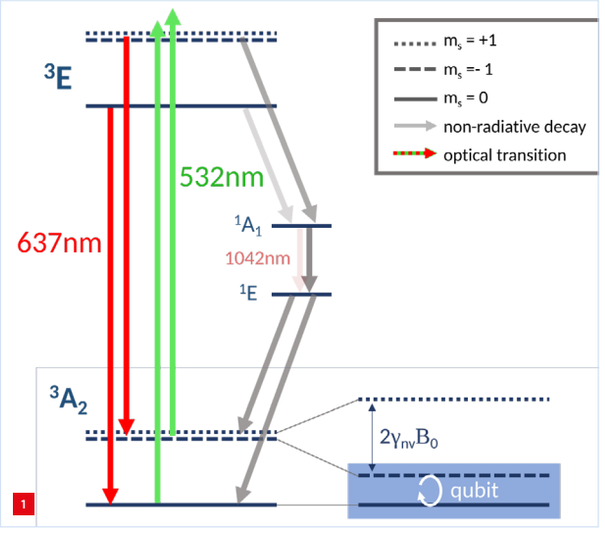
The CryoStage aligns a device below the probe card and establishes probe contact. The statically determined gantry design allows long-stroke positioning across a 150-mm wafer, small orientation corrections of ±2°, sub-micrometer resolution, and micrometer-level alignment accuracy and stability. A vertical motion mechanism makes or releases probe contact. The stage must remain accurate after cooling

SPIN, SHINE, SENSE

Nitrogen-vacancy (NV) centres in diamond are practical room-temperature quantum sensors that can measure magnetic fields through optically detected magnetic resonance (ODMR). At Saxion University of Applied Sciences, we realised a free-space continuous-wave ODMR platform and quantified its magnetic-field sensitivity. We systematically studied the key subsystems, being microwave antenna, low-noise photodetection and lock-in read-out, with a clear focus on real-world device requirements and deployment. The resulting modular, 3D-printed demonstrator combines electronics and photonics with modest infrastructure. The accumulated expertise now supports the development of higher-sensitivity sensors that can operate in real-world noisy environments.

TJEERD BOLLMANN

Quantum technology rests on three pillars that are rapidly moving from laboratory curiosity to engineered systems: quantum computing, quantum communication and quantum sensing. Quantum computers promise to solve specific problems that are very time-consuming for classical machines by exploiting superposition and entanglement. Quantum communication aims to distribute information with security guaranteed in the laws of physics. Quantum sensing, the focus of this article, uses the extreme sensitivity of quantum states to measure physical quantities, for example magnetic field, temperature or electric field, with high precision, often at room temperature and in compact designs.



Energy levels and optical cycle of the NV^- centre in diamond. Green light excites the centre from the ground state to the excited state (spin is mostly conserved). From the excited state, the centre can return by emitting red fluorescence or by taking a darker, non-radiative path through intermediate singlet levels. The darker path is preferred when the spin is in the $m_s = \pm 1$ states, so the red fluorescence becomes weaker. A static magnetic field B_0 shifts the $m_s = \pm 1$ levels (Zeeman effect); the microwave frequency needed to flip the spin therefore changes with the field. Measuring the frequency at which the fluorescence drops gives the local magnetic field (ODMR). (Adapted from wikimedia, user BonPhire, https://commons.wikimedia.org/w/index.php?curid=100274313).

AUTHOR'S NOTE
Tjeerd Bollmann is a senior researcher at Saxion University of Applied Sciences, located in Enschede (NL). Within the Applied Nanotechnology research group, he initiated the quantum-photonics activities, hosted in the Talent and Learning Centre, where students, researchers and companies from the regional ecosystem collaborate. The work is supported by QDNL.

In addition, he developed and leads the joint master's programme Applied Quantum Technology for Saxion and is one of lecturers in the programme.

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At Saxion, we chose quantum sensing with nitrogen-vacancy (NV) centres in diamond as our first research line three years ago, precisely because the technology sits at the intersection of electronics and photonics while requiring only modest laboratory infrastructure, as we did not have, for example, access to cryogenic infrastructure at the time. Today, this technology already gives optically readable vector magnetic sensing; by applying more advanced quantum protocols on the same hardware it can later reach (and in specific cases exceed) the precision of existing classical sensors.

The same experimental platform that detects magnetic fields can also be used to drive and observe, for example, Rabi oscillations, which is the coherent flipping of a spin qubit under a resonant microwave field. Rabi oscillations are one of the most basic tools for the characterisation of qubits for quantum computing; mastering this technology therefore opens a natural pathway from sensing towards quantum information science.

Over the past three years, we guided several successive cohorts of students, interns, graduates and fellow researchers in building, characterising and improving a free-space continuous-wave optically detected magnetic resonance (ODMR) platform, as described below. The accumulated know-how is now being carried forward into the PREVENT project, joining forces between four universities of applied sciences (Hogeschool van Amsterdam, Saxion, Haagse Hogeschool and Fontys), financed by Holland High Tech, where the emphasis shifts to higher-sensitivity devices that can function in the noisy environments of real-world applications.

Quantum sensor at room temperature

An NV centre is an atomic-scale defect in the diamond lattice: a nitrogen atom sitting next to a vacant lattice site [1]. In its negatively charged state (NV^-), the defect behaves like a tiny, optically readable compass. Its (overall) electron spin can –

presented in simplified form – point in three directions (labelled $m_s = 0, +1$ and -1); see Figure 1. The diagram shows the energy levels of a nitrogen-vacancy (NV) centre in diamond.

Green laser light excites the centre, shifting electrons from the ground state ($^3A_2$) towards the excited state (^3E) (both being triplet states). From there, the excited electron can return to the ground state ($^3A_2$) either by emitting red fluorescence or by taking a darker, non-radiative path via $^1A_1$ and ^1E. Which path it prefers depends on its electron spin ($m_s = 0, +1$ or -1), $m_s = +1$ or -1 being more likely to take the non-radiative path. These discrete spin states, $m_s = 0, +1$ or -1, are quantum in nature: they can be prepared and flipped with help of the right energy, being the microwaves here. An additional external magnetic field shifts the ±1 levels via the Zeeman effect, changing the microwave frequency needed for the flip. When the microwave is on resonance the fluorescence drops, so the frequency of the dip directly relates to the local magnetic field, which is the ODMR principle.

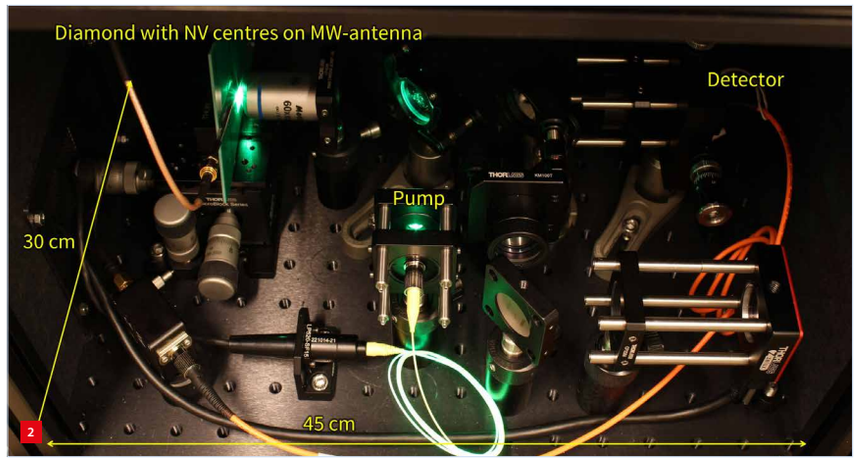
Building the optical and microwave platform

The energy-level structure of the NV^- centre (Figure 1) provides the spectroscopic foundation. Optical excitation from the ground-state spin sub-levels proceeds at different rates into the excited state; inter-system crossing preferentially returns population from the ±1 states into a metastable singlet (the energy levels at the right in Figure 1), reducing the subsequent fluorescence. Microwave driving between 0 and ±1 therefore modulates the observed photoluminescence and yields the characteristic ODMR dips (see below, Figure 4).

The experimental realisation (Figure 2) is a free-space optical path in which a green laser acting as the pump (labelled as such in the figure) is focused via a (dichroic) mirror and microscope objective onto a diamond sample containing an ensemble (hence lots) of NV^- centres (top left of the figure). Fluorescence reflecting from it is collected, filtered and directed (through the dichroic mirror) onto the (photo)detector (labelled 'detector' in the right of the figure), while a microwave field is delivered by a nearby antenna (the green printed circuit board (PCB) at the top left). A static bias field (B_0), which is omnipresent as the earth's magnetic field of about 50 microTesla, splits the ±1 levels and enables our magnetometer.

For changing the magnetic field present around the NV^- centres, we designed a solenoid over the microscopy objective to convert current into a controlled magnetic field over the optical axis. Figure 3 illustrates the design of the solenoid coil, the 3D-printed cover for mounting over the microscopy objective, and the assembled solenoid magnet having 63 turns of 0.5 mm enamelled copper wire.

Figure 4a illustrates a typical continuous-wave ODMR spectrum recorded with a bias current (and therefore external magnetic field), to which we fitted a multi-Lorentzian in order to extract the



Laboratory free-space optically (FSO) detected magnetic resonance set-up showing the confocal optical path, where the laser acts as a pump, the diamond sample is placed on top of the microwave (MW) PCB antenna, and the resulting fluorescence is captured on the (photo)detector. The total dimensions of the set-up are about 30 cm x 45 cm x 30 cm.

The solenoid.
(a) CAD model of the solenoid coil.
(b) 3D-printed mounting structure over the objective.
(c) Fabricated solenoid coil used to calibrate the magnetic field as a function of coil current.

precise ODMR frequencies. The fluorescence typically drops by about 1% of intensity on the ODMR dips (see the y-axis in Figure 4a). We calibrated the solenoid for its resulting magnetic external field generated by the applied current running through it.

Stacking many such ODMR spectra, where we varied the current on the solenoid, hence controlling the external magnetic field, we produced a two-dimensional fluorescence heatmap versus microwave frequency and applied magnetic field (Figure 4b). Four resonance branches were clearly resolved, corresponding to the two electron-spin projections and the two distinct crystallographic orientations present in our diamond. Multi-Lorentzian fits were used to extract the precise frequencies of each of the resonances. Plotting these frequencies against the applied magnetic field and performing a linear regression then yielded the effective Zeeman slope (in GHz/T) for every branch. From the small residual offset of these fits, we could also correct for a modest calibration error in the resulting magnetic field (B_1) from the solenoid that converts applied current into magnetic field.

In order to obtain the sensitivity of our experimental set-up, we determined the frequency uncertainty δf obtained from the residual scatter of the linear fits, normalised by the square root of the integration time. The resulting magnetic-field sensitivity fell