Diamond-based quantum sensors in defence and security applications

P. Knittel*, P. Haas, N. Lang, N. Mathes, V. Cimalla, M. Kunzer

Fraunhofer Institute for Applied Solid State Physics, Tullastraße 72, 79108 Freiburg, Germany
*peter.knittel@iaf.fraunhofer.de; phone +49 761 5159-324; iaf.fraunhofer.de

ABSTRACT

Many quantum technologies are dual-use technologies that can introduce new capabilities to defence and security-related applications or increase their effectiveness. In particular, diamond-based quantum sensors have great potential due to the high robustness of this material in conjunction with quantum effects accessible at room temperature. The negatively charged nitrogen vacancy centre (NV^-), an atomic defect within the diamond matrix, carries an electron spin that can be actively addressed and read-out via optical and electrical means at room temperature. This electron spin is highly sensitive to external magnetic fields, temperature, and pressure and thus well-suited for quantum sensing in defence and security.

Nowadays, diamond is reliably produced by means of chemical vapour deposition, allowing for tailored sensor elements, such as with oriented NV centres in layers and in microstructures that are highly interesting for vector magnetometry. Sensitive magnetometry is useful in global magnetic navigation, detecting metallic objects like submarines, human-machine interfaces and more. Apart from that, radiofrequency signals are detected in real-time with GHz spectral coverage in radar analysis. Recently, the use of these diamond-based quantum sensing technologies for side-channel attacks has come into focus, for example, to gather information on implementation of algorithms for cryptosystems. These technologies are introduced along with the fabrication of the underlying diamond sensor element.

Keywords: diamond, nitrogen vacancy centres, magnetometry, radio frequency sensing, side-channel attack

1. INTRODUCTION AND BACKGROUND

The unique properties of diamond, being the hardest natural material known, as well as its high thermal conductivity, optical transparency and chemical inertness, have made it a focus of researchers for many years already. Today, the high thermal conductivity of diamond is used in heat spreaders for GaN-based devices in radar and high-power applications [1]. In recent years, diamond has gained increasing attention because of its luminescent defects often referred to as colour centres that can be used as minute, atomic-sized sensor elements. Among these colour centres, the most studied one is the negatively charged nitrogen vacancy (NV^-) centre, which is a substitutional nitrogen atom with a vacancy next to it that carries an additional electron [2]. The spin state of this electron can be actively initialised and read out by optical means at room temperature. Given that the electron spin is highly susceptible to changes in its surroundings, it can be used to determine variations in temperature, pressure, and magnetic fields. Especially the latter makes it an interesting candidate for detecting minute magnetic fields, e.g., in magnetic anomaly detection for positioning systems not relying on global navigation satellite systems (GNSS) [3]. The magnetic field sensing is calibration-free and due to the four possible orientations of the NV centre in diamond, single-chip vector magnetometry can be conducted without further modifications.

The underlying principle using NV centres in diamond for sensing is depicted in Figure 1. The colour centre exhibits a spin-1 system with ground states m_s 0 and two degenerate states m_s ±1 separated by 2.87 GHz at zero magnetic field. When the NV centre is excited into its excited states, intersystem crossing to the singlet state eventually occurs. This process has a higher probability from the m_s ±1 excited state, as well as the intersystem crossing from the singlet state to the m_s 0 ground state (indicated by the bold black arrows). Due to this favoured process, the NV centre can be initialised in the m_s 0 ground state just by optical pumping and further manipulated using microwaves. In addition, the spin state can be read out by optical means (optically detected magnetic resonance, ODMR) due to this process, as the intersystem crossing results in a decreased red fluorescence. This decrease can be as high as 30% when the spin is actively driven into the m_s ±1 state [4]. As the m_s ±1 state is degenerate, it undergoes Zeeman splitting when a magnetic field is applied. As a result, the microwave frequency to drive the system into the m_s +1 or -1 state shifts to higher and lower values,

Quantum Technologies for Defence and Security, edited by Giacomo Sorelli,
Sara Ducci, Sylvain Schwartz, Proc. of SPIE Vol. 13202, 132020B
 · doi: 10.1117/12.3038043

respectively, allowing for an accurate determination of the applied magnetic field without further calibration, as the splitting is readily described by the gyromagnetic ratio γ of the electron. Another read-out mechanism that was developed in the last years is the photoelectrical detection scheme (PDMR) where the magnetic field dependent photocurrent is measured [5].

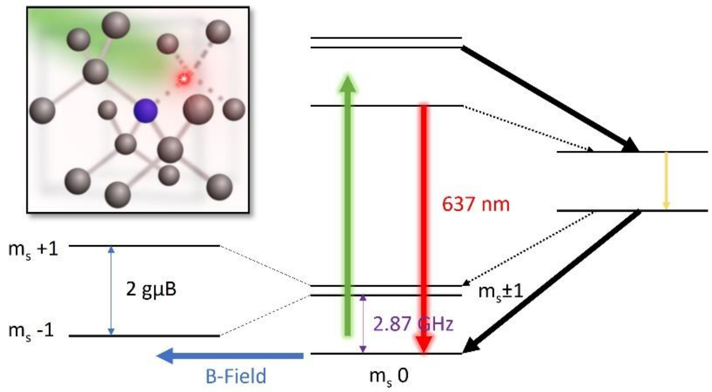

Figure 1. Schematic representation of the NV centre in diamond and the corresponding level scheme showing the emission wavelengths under excitation, the microwave frequency to excite the spin to the degenerate m_s ±1 state after initialisation and the Zeeman splitting of this state when applying a magnetic field.

To make use of the described characteristics and manufacture a diamond-based quantum sensor, the creation of these colour centre as well as their placement in the crystal and the shape of the diamond for effective in- and out-coupling must be controlled. This can be achieved by means of chemical vapour deposition (CVD) of diamond films.

2. DIAMOND SENSOR FABRICATION

When using CVD for diamond synthesis, high-purity diamond films can be obtained. These films can be further used for implantation of nitrogen to generate NV centres [6]. Due to the accurate control of ions integrated into the diamond matrix, implantation is especially useful when single NV centres are needed for high-resolution sensing applications, such as scanning probe techniques. However, this process can lead to significant damage to the diamond matrix, compromising sensing performance of the NV centres [7]. In particular, for higher implantation doses, when ensembles of NV centres are targeted, this is a major disadvantage. In defence-related applications, ensemble NVs play a more important role due to their higher signal intensity and the resulting greater robustness of the measurement signals. Ensemble NVs can be obtained by doping the diamond films with nitrogen during CVD growth. During growth, approximately 0.3% of the substitutional nitrogen is incorporated in the form of NV centres. This results in typical NV concentrations in the ppb range [8]. When using specific substrate orientations like (111), these NV centres are even created in a preferential alignment. Higher NV concentrations can be achieved by generating of additional vacancies in the crystal, for example, by electron irradiation in conjunction with annealing the crystal to make the vacancies mobile and associate them with substitutional nitrogen. In this way, concentrations in the ppm range are readily obtained.

We employ this technique for the fabrication of several 100 nm thin films on the surface of the diamond to obtain a sensitive layer with an NV concentration in the range of 1 ppm, e.g., for wide-field magnetometry. One of these films is shown in Figure 2. Such layered growth approaches allow for precise positioning of NV centres at a specific depth. For quantum sensing applications that require a bulk NV-containing diamond, the growth can be extended for a longer timeframe.
Additionally, there are strategies to position the NV centres laterally on pyramidal structures [9] or in predefined defects in diamond [10] by using growth conditions that promote growth in crystal orientations other than the used substrate as shown in Figure 3. With the former approach, pyramids with all four NV orientations laterally separated on the four

flanks of the pyramid can be obtained. This makes them individually addressable by positioning the detection focus accordingly, facilitating vector magnetometry measurements without the need of a large bias-field to spectrally separate the individual NV orientations. The latter approach enables the production of polished diamond surfaces containing NV centres in well-defined areas that can have dimensions below the diffraction limit of optical systems.
These approaches can be used individually or combined to provide the sensor core in quantum sensing systems based on diamonds. In addition, the diamonds can be macroscopically shaped to improve light in- and out-coupling [11]. This is readily achieved using precise laser cutting tools.

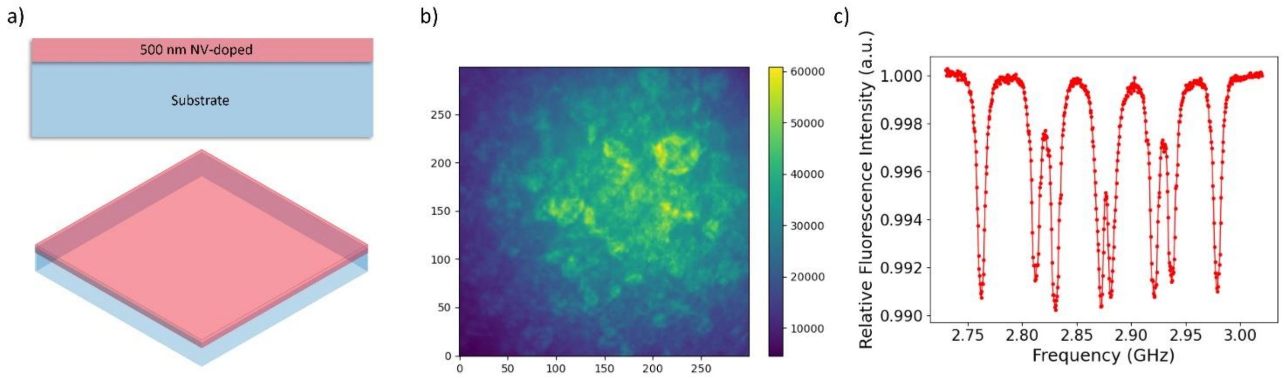

Figure 2. a) Layer structure of the diamond used for ODMR experiments with an ultrapure substrate and a NV-doped layer on top. b) PL image of the film showing emission from NV centres with highest intensities in the centre of the laser spot. c) ODMR measurement of the layer under applied magnetic field exhibiting eight fluorescence dips due to the four possible orientations of the NV centre in diamond.

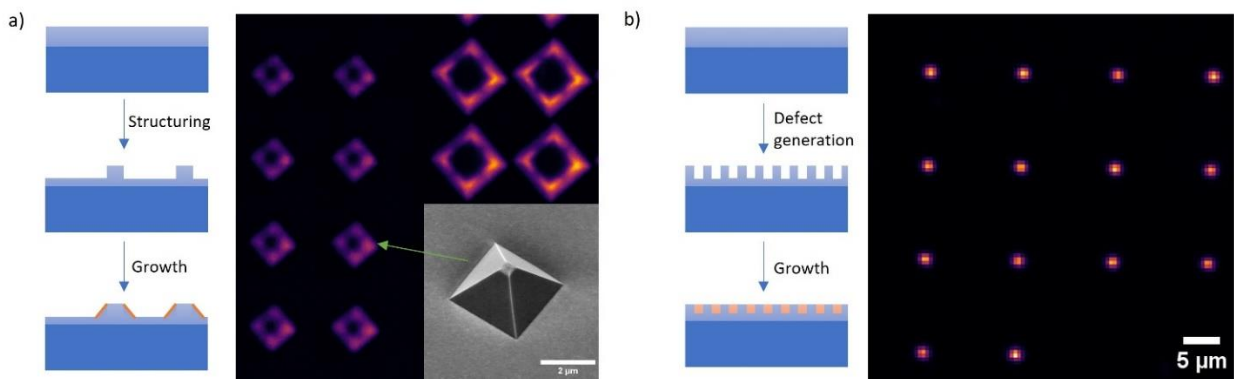

Figure 3. Strategies for lateral positioning of NV centers: a) Fabrication of pyramids containing NV centers with defined orientation on the pyramid flank. b) Defect removal by local growth and formation of positioned NV ensembles in these areas.

3. MAGNETOMETRY

Detecting magnetic fields in proximity to the NV centres is probably the most studied application in recent decades. Given that the system is calibration-free and can be easily read out with high sensitivity at room temperature by optical means, this approach is used to detect minute magnetic fields in proximity to the NV sensor. One example of recording the magnetic domains of a floppy disk is shown in Figure 4. Using diamond films as shown in Figure 2, this image can be recorded in wide-field magnetometry within a few seconds by employing a CCD camera to detect the fluorescence intensity while driving the NV center at a microwave frequency adjusted to the corresponding magnetic field of the floppy disk's magnetic material. A detailed description of the system used can be found in a recent publication [12].

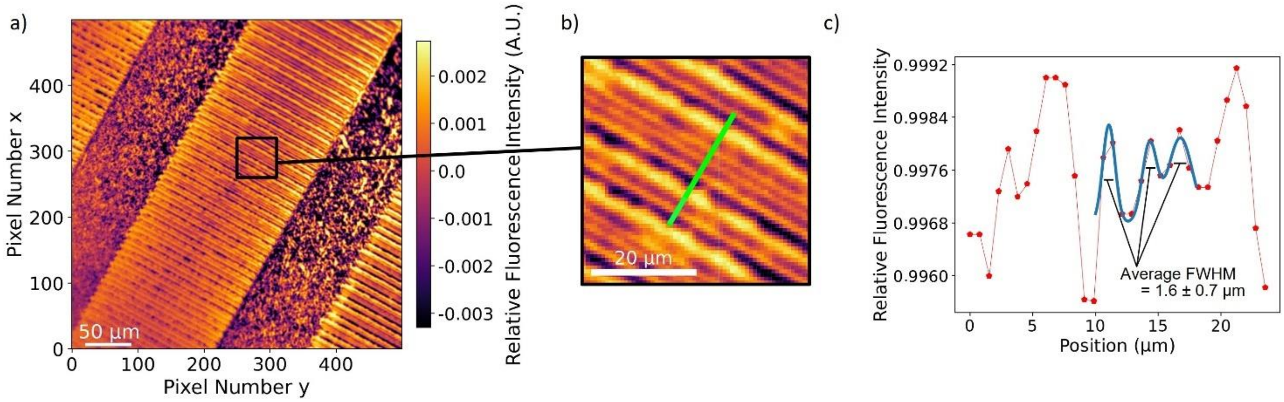

Figure 4. Magnetic field mapping of a floppy disk: a) overview scan on the magnetic domains. b) Zoomed view of a data containing region where individual bits are encoded based on the magnetization shown in c).

In this application, the combination of measurement speed and spatial resolution is employed to characterize minute magnetic fields on a microscopic level. This can be used to inspect magnetic materials quickly and may even allow the detection of developing fatigue cracks in metallic alloys. Additionally, the system can be used to map currents in electronic circuits by detecting the induced magnetic field of the current flowing through them. This paves the way for quickly detecting failures in microelectronic devices. It may be used to determine active regions and the emitted signals, such as timings in microchips used in encryption, to design possible attack vectors for side-channel attacks.

The same measurement principle applies for larger-scale magnetometers where the overall magnetic field acting on the diamond sensor is measured. To date, sensitivities below the pT range have been achieved [13]. These magnetometers can be used in defence applications to detect minute magnetic anomalies (MAD) for GNSS-free navigation purposes [3]. They also allows for detecting magnetic objects like submarines, underground installations, and explosive devices. In addition, further sensitivity improvements may lead to the detection of muscle or brain activities that can be used to construct human-machine interfaces (HMI).

4. RADIO FREQUENCY SENSING

From Figure 2 it is evident, that the splitting observed in ODMR is dependent on the magnetic field imposed on the NV centre. Due to the different orientations, the NV centres show different splitting depending on the intensity of the magnetic field component aligned along their specific axes and hence they are driven at different microwave frequencies. Inverting the principle of magnetometry with NVs, this can be used to detect radio frequency (RF) signals from a few MHz up to 25 GHz [14]. This is achieved using a calibrated bias magnetic field and a detector that allows for local detection of the fluorescence signal on the diamond chip. Each NV centre location then corresponds to a specific frequency defined by the bias magnetic field.

We use a diamond with a NV ensemble concentration of approx. 0.3 ppb with (100) orientation of the main facet and (110) orientation on the side facets to implement this technique. The 532 nm excitation laser is fed through the side facet to achieve a linear illumination path along the magnetic field gradient. To collect the red fluorescence a 5x microscopy lens is used and detected with a CCD camera. This provides insight into more than 1000 frequency channels on the sensor chip [15].

The passive interception, localization, and analysis of RF signals are key features of electronic intelligence (ELINT). Hence, spectral analysers with a large tuning range of up to 10 GHz and an instantaneous detection range of several GHz are required. The NV diamond quantum signal analyser described above has the potential to overcome these challenges. Compared to current ELINT spectral analysers, it utilizes a hardware-based approach to directly provide a frequency spectrum from the sensor chip. Furthermore, a fast and continuous optical readout of the RF sensor is realized via a high speed and high dynamic CCD camera. Frequency modulated continuous wave (FMCW) radars are of increasing importance since they are easy and cost effective to implement with modern semiconductor technology. Lacking any pulses due to their CW nature, they are difficult to intercept and all information and processing is within the frequency domain only [16].

To demonstrate the capability of the NV diamond RF signal analyser, an FMCW radar signal is fed into the sensor. The optical readout of the diamond quantum sensor captured with a CCD-line camera is plotted in Figure 5. No post processing has been applied. The left part of Figure 5 shows the spectrogram of the signal in the S band with a centre frequency of 2.25 GHz and a frequency modulation of 300 MHz. The technical parameters and thus the signature can be directly determined from the spectrogram. A magnification of the time scale shows that the signal is composed of individual 10 MHz frequency steps, each 2 ms long. These signature parameters can be used to classify the radar source, deduce information such as location and relative speed or to prepare specific countermeasures.

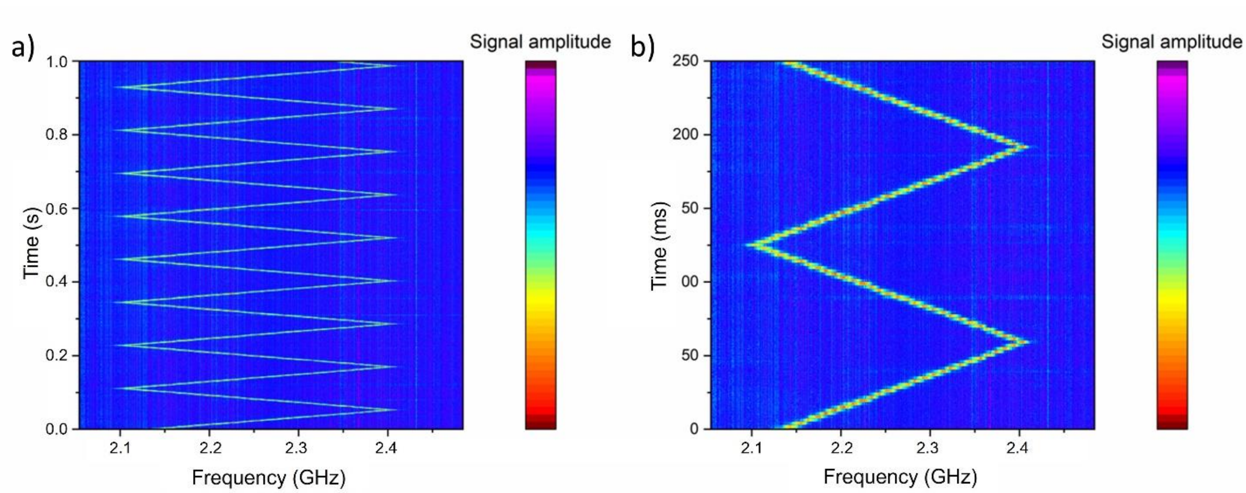

Figure 5. Spectrogram of an FMCW-like RF signal. A zoom of the time scale (right diagram) reveals a 300 MHz frequency modulation composed of 10 MHz frequency steps each 2 ms.

Apart from the direct interception of RF signals, this approach can also be used in cybersecurity applications where RF signals from microchips are locally detected.

5. CONCLUSION AND OUTLOOK

Today, sensor elements based on the NV centres in diamond can be readily produced by CVD synthesis of diamond films in a reliable manner. This paves the way for reproducible and scalable fabrication of diamond-based quantum sensors. Given the robustness of the material in conjunction with the excellent sensing properties, these sensors are a promising platform for defence and security applications that require high mobility. Quantum magnetometry based on diamond is promising for global and local navigation, the detection of metallic objects like submarines or wrecks, and for interfacing biological signals with machines to build HMIs. Especially the capability to conduct vector magnetometry making use of the four possible orientations of NV centres in diamond in a simple approach is highly attractive. The described RF sensing scheme based on diamond can be applied in intercepting communication channels as well as frequency agile radar signals. Both described approaches may also find their way into cybersecurity applications when employed in side-channel attack scenarios in the future. Apart from these described applications, there is another technique that is actively being developed and should be mentioned in the context of defence applications, which is the NV-based gyroscope [17].

ACKNOWLEDGEMENTS

This project has received funding from the European Defence Fund (EDF) under grant agreement 101103417 EDF-2021-DIS-RDIS-ADEQUADE and funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101080136 (AMADEUS).

DISCLAIMER

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the granting authority can be held responsible for them.

REFERENCES

[1] L. Sang, "Diamond as the heat spreader for the thermal dissipation of GaN-based electronic devices," Funct. Diam. **1**(1), 174–188, Taylor & Francis (2021) [doi:10.1080/26941112.2021.1980356].

[2] A. Gruber et al., "Scanning Confocal Optical Microscopy on Single Defect Centers," Science (80-.). **276**(5321), 2012 (1997).

[3] T. Fleig and P. Frontera, "Maritime magnetic anomaly mapping with a diamond nitrogen vacancy sensor," in 2018 IEEE/ION Position, Location and Navigation Symposium (PLANS), pp. 1107–1112, IEEE (2018) [doi:10.1109/PLANS.2018.8373493].

[4] Z. Yuan et al., "Charge state dynamics and optically detected electron spin resonance contrast of shallow nitrogen-vacancy centers in diamond," Phys. Rev. Res. **2**(3), 1–11, American Physical Society (2020) [doi:10.1103/physrevresearch.2.033263].

[5] E. Bourgeois et al., "Photoelectric detection of electron spin resonance of nitrogen-vacancy centres in diamond," Nat. Commun. **6**(1), 8577, Nature Publishing Group (2015) [doi:10.1038/ncomms9577].

[6] T. Chakraborty et al., "CVD growth of ultrapure diamond, generation of NV centers by ion implantation, and their spectroscopic characterization for quantum technological applications," Phys. Rev. Mater. **3**(6), 1–11, American Physical Society (2019) [doi:10.1103/PhysRevMaterials.3.065205].

[7] S. B. van Dam et al., "Optical coherence of diamond nitrogen-vacancy centers formed by ion implantation and annealing," Phys. Rev. B **99**(16), 161203, American Physical Society (2019) [doi:10.1103/PhysRevB.99.161203].

[8] T. Luo et al., "Creation of nitrogen-vacancy centers in chemical vapor deposition diamond for sensing applications," New J. Phys. **24**(3), 033030 (2022) [doi:10.1088/1367-2630/ac58b6].

[9] A. Götze et al., "Preferential Placement of Aligned NV Centers in CVD-Overgrown Diamond Microstructures," Phys. status solidi – Rapid Res. Lett., pssr.202100373 (2021) [doi:10.1002/pssr.202100373].

[10] N. Lang et al., "Controlled lateral positioning of NV centres in diamond by CVD overgrowth," Phys. Scr. **29**(46), 465705 (2024) [doi:10.1088/1402-4896/ad6f60].

[11] R. D. Allert et al., "Microfluidic quantum sensing platform for lab-on-a-chip applications," Lab Chip **22**(24) (2022) [doi:10.1039/d2lc00874b].

[12] N. Mathes et al., "Nitrogen-vacancy center magnetic imaging of Fe 3 O 4 nanoparticles inside the gastrointestinal tract of Drosophila melanogaster," Nanoscale Adv. **6**(1), 247–255, Royal Society of Chemistry (2024) [doi:10.1039/D3NA00684K].

[13] T. Wolf et al., "Subpicotesla Diamond Magnetometry," Phys. Rev. X **5**(4), 041001 (2015) [doi:10.1103/PhysRevX.5.041001].

[14] S. Magaletti et al., "A quantum radio frequency signal analyzer based on nitrogen vacancy centers in diamond," Commun. Eng. **1**(1), 19, Springer US (2022) [doi:10.1038/s44172-022-00017-4].

[15] D. Karcher, *Master Thesis, Fraunhofer IAF and IPQ* (2020).

[16] M. Kunzer, "Diamond-based Quantum Sensing for RF Signal Analysis," Proc. 10th Mil. Sens. Symp., STO – MP – SET – 311 (2023).

[17] A. Jarmola et al., "Demonstration of diamond nuclear spin gyroscope," Sci. Adv. **7**(43), 3–7 (2021) [doi:10.1126/sciadv.abl3840].