Principles of Scanning Nitrogen-Vacancy Magnetometry Explained

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Scanning nitrogen-vacancy (NV) magnetometry is a measurement technique that combines scanned probe microscopy (SPM) with optically detected magnetic resonance (ODMR) to image magnetic field distribution with high spatial resolution (<50 nm). This technique advances our understanding of the physics of nanomagnets in condensed matter physics and cell biology.

What Scanning NV Magnetometry Can (and Cannot) Do

Scanning NV magnetometry "relies on a single, optically-readable defect spin [i.e., an NV center] embedded in a sharp diamond tip that is scanned over the sample of interest."[1] While this technique has been applied to measure the temperature and electrical field, this article focuses mainly on its ability to detect very weak magnetic fields, of the order of micro-Tesla.

Scanning NV magnetometry is commonly applied in two different ways. The first type of measurement, called a pulsed measurement (such as relaxometry), is extremely sensitive but very slow. It can detect the magnetic moment of nuclear spins, but the measurements can take several hours and thus are not often used for imaging.

Continuous wave (CW) scanning NV magnetometry, meanwhile, is less sensitive but is relatively fast, recording a single data point within a few seconds. CW scanning NV magnetometry is more popular for this reason and is used for a multitude of engineering and scientific applications.

For example, a researcher may wish to map the magnetic field distribution generated by current across a sheet of graphene. The experiment does not require single-molecule-level resolution; a CW measurement is capable of the 40-50 nm resolution necessary (to image a single molecule, <10 nm resolution would be required). As current is applied to the graphene sheet, the magnetic field generated can be gauged using the NV center (i.e., the probe tip). In a microchip, this is how heat signature can be determined. The more heat a component generates, the more likely it is to encounter problems. Less current applied to the chip means less magnetic field is generated, but it remains detectable with 50 nm resolution.

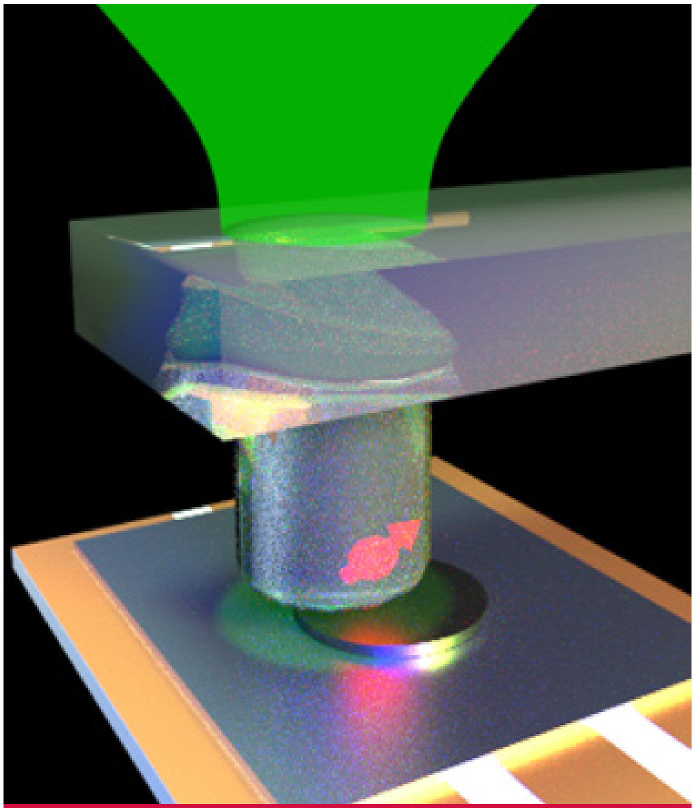

Fig 1: *This rendering of scanning NV magnetometry depicts a scanning diamond probe tip, with NV center spin, above a sample. Optical excitation using a green laser is above the scanning probe. Two microstrip lines for MW generation are shown at the sample.*

CW scanning NV magnetometry can be applied to understand how magnetism functions at various scales relevant to new materials (e.g., two-dimensional magnetic materials — literally two atomic layers — which are important in the field of on-chip quantum communication and magnetic memory devices). [2] CW scanning can create a large (e.g., 500x500 pixel) image with very high spatial resolution at about 50 nm. The technique will capture individual domains, structures/boundaries between the domains, and how the domains work and move. It can provide a high-quality image within two or three hours, allowing analysis of a material to be completed within a day.

Other techniques, including using a scanning tunneling microscope (STM), which provides sub-nanometer resolution, can supplement the data provided by scanning NV magnetometry. Each is accompanied by advantages and disadvantages.

For example, the most sensitive magnetic field detection technique is a superconducting quantum interference device (SQUID), making it an appropriate tool when detecting a weak magnetic field is more important than high spatial resolution. However, measurements must be taken at low temperature and a SQUID system can cost up to five times more than a scanning NV magnetometry system. An STM apparatus, too, costs more than a standard scanning NV magnetometry system.

Scanning NV magnetometry might not achieve atomic scale resolution, but it provides very high spatial resolution and acceptable magnetic sensitivity compared with these other techniques.

What Instrumentation and Conditions are Required to Conduct Scanning NV Magnetometry?

First, a scanning probe microscope (SPM) is required. The SPM is equipped with a diamond tip containing a one-atom defect (i.e., the nitrogen-vacancy) that interacts with the sample. In recent years, NV center-equipped tips compatible with an SPM have become commercially available.

Second, scanning NV magnetometry requires an optical detection setup — its key differentiator versus similar techniques. A typical SPM detects electrically or gauges surface force to map surface topography. Scanning NV magnetometry measures a magnetic field by shining a green light on the diamond probe tip, prompting the NV center tip to emit red light. From that red light signal, the user can determine the magnetic field at the position of the tip. By moving from position to position and repeating the measurement to collect more magnetic field data, the user accomplishes two tasks simultaneously: determining the sample's surface topography and measuring the magnetic field distribution at the surface.

Like any scanning probe technique, scanning NV magnetometry requires a vibration-free environment to function optimally, generally accomplished using an air table and one or more positioning systems to create a stable surface. At very high resolutions, all vibrations in the lab environment (e.g., HVAC air movement and sound vibration) must be addressed, so they do not impact experiments. Additionally, since scanning NV magnetometry comprises an optical measurement, stray light (e.g., from lab lamps) can interfere with its results.

Comparatively speaking, scanning NV magnetometry requires less work and environmental preparation than, for example, scanning SQUID techniques, wherein measurements must be taken at a low temperature and require the entire system to be isolated. Scanning NV magnetometry is user-friendly in that detection occurs at room temperature. This also renders it advantageous versus other techniques in the study of living cells as researchers must maintain a living environment. Because the diamond is chemically inert and does not require low temperature, it is highly compatible with biomolecules.

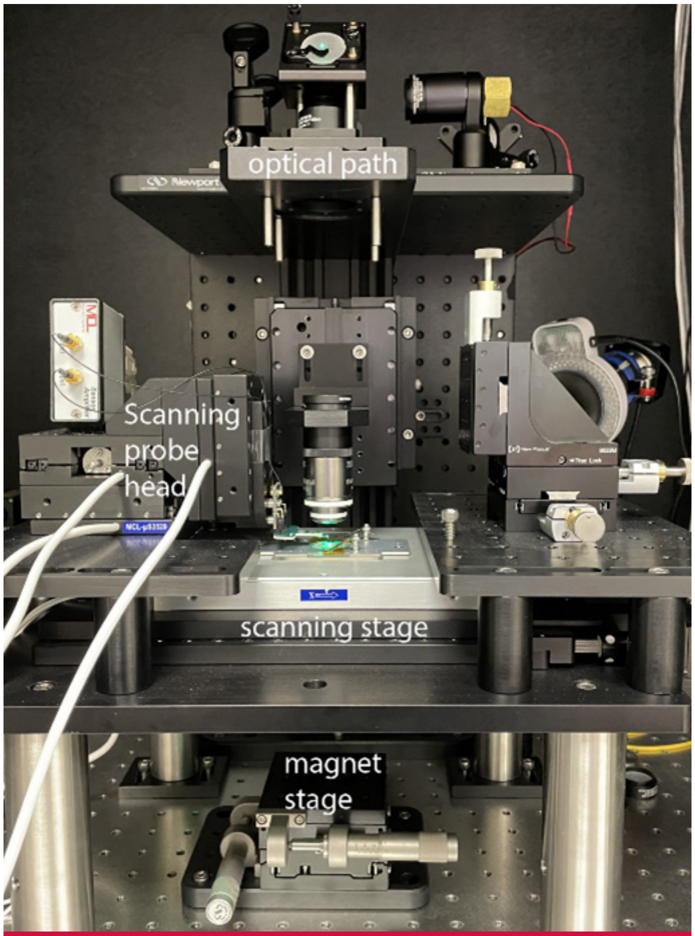

***Fig 2:** This custom scanning NV magnetometry instrument utilizes a Mad City Labs scanning probe microscope fitted into the existing optical setup.*

Final Thoughts

Magnetic field sensing is critical to metrological applications. It can help to pinpoint defective regions in semiconductor chips and helps us to understand new materials (e.g., two monolayers versus three monolayers). It may also be applied to understand how different structures, as small as <100 nm, behave when creating a device.

Though this article focuses on scanning NV-based magnetic field sensing, NV center-based magnetometry also can be applied to understanding how neurons send signals to navigation (e.g., GPS, drone) technology. Consider that satellite navigation can be jammed, but a technique that relies on detection of the earth's magnetic field cannot be so easily undermined.

When scanning NV magnetometry was first developed about a decade ago, researchers required deep expertise to apply the technique. Only recently has the instrumentation required become more intuitive to use and more commercially available, greatly expanding the opportunities for scanning NV magnetometry's application in numerous areas of research, and progress continues. That said, it is relatively simple to build a scanning NV magnetometry microscope from a resonant probe AFM.[3,4] In many ways, developing a custom instrument is desirable since scanning NV magnetometry is useful across a range of applications with differing instrument requirements.

At its inception, scanning NV magnetometry instrumentation was very complex, and producing a single image could take around five hours; even today, collecting a single data point using pulsed measurement can take up to a few hours. From a scientific standpoint, the time required may be less relevant, so long as the data is accurate, but for this technique to be applied more commonly in industrial applications (e.g., to check a device quickly and, according to that data, correct a fabrication process), solutions are being explored to speed up that process without compromising resolution. Significant advances also are being made in the techniques and technologies used to make NV center tips.

To learn more, contact the author and visit madcitylabs.com.

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About The Author

Dr. Kapildeb Ambal is an Assistant Professor of Physics at Wichita State University. He received a B.Sc. with Honors in Physics from the University of Calcutta, India, an M.Sc. in Physics from the Indian Institute of Technology Madras, India, and an M.S. and a Ph.D. in Physics from the University of Utah. His doctoral research focused on imaging and spectroscopy of individual paramagnetic electronic states on the atomic scale. Before joining Wichita State University, he was a postdoctoral researcher at the University of Maryland and guest researcher at the National Institute of Standards and Technology (NIST), where he worked on the probing of magnetization dynamics of nanomagnets. He is currently working on the investigation of spin-dependent electronic processes at the nanoscale in condensed matter systems to reveal the mesoscale physics that control charge and spin motion.

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