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Sensing and controlling microscopic spin density in materials

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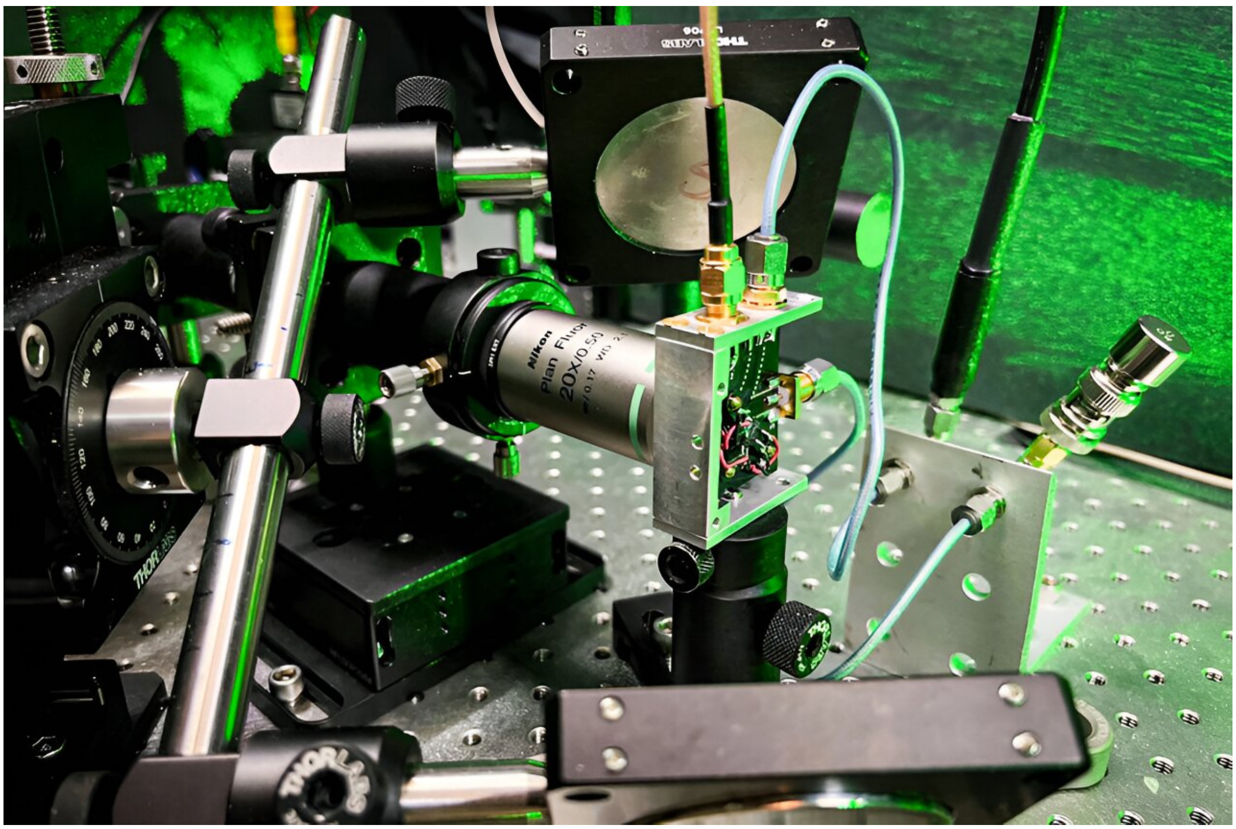

MIT researchers found a way to tune the spin density in diamond by applying an external laser or microwave beam. The finding could open new possibilities for advanced quantum devices. Pictured is a view of the laser equipment used in the researchers' work. Credit: Courtesy of the researchers

Electronic devices typically use the charge of electrons, but spin—their other degree of freedom—is starting to be exploited. Spin defects make crystalline materials highly useful for quantum-based devices such as ultrasensitive quantum sensors, quantum memory devices, or systems for simulating the physics of quantum effects. Varying the spin density in semiconductors can lead to new properties in a material—something researchers have long wanted to explore—but this density is usually fleeting and elusive, thus hard to measure and control locally.

Now, a team of researchers at MIT and elsewhere has found a way to tune the spin density in diamond, changing it by a factor of two, by applying an external laser or microwave beam. The finding, reported in the journal *PNAS*, could open up many new possibilities for advanced quantum devices, the authors say. The paper is a collaboration between current and former students of professors Paola Cappellaro and Ju Li at MIT, and collaborators at Politecnico of Milano.

The first author of the paper, Guoqing Wang Ph.D. '23, worked on his Ph.D. thesis in Cappellaro's lab and is now a postdoc at MIT.

A specific type of spin defect known as a nitrogen vacancy (NV) center in diamond is one of the most widely studied systems for its potential use in a wide variety of quantum applications. The spin of NV centers is sensitive to any physical, electrical, or optical disturbance, making them potentially highly sensitive detectors.

"Solid-state spin defects are one of the most promising quantum platforms," Wang says, partly because they can work under ambient, room-temperature conditions. Many other quantum systems require ultracold or other specialized environments.

"The nanoscale sensing capabilities of NV centers makes them promising for probing the dynamics in their spin environment, manifesting rich quantum many body physics yet to be understood," Wang adds. "A major spin defect in the environment, called P1 center, can usually be 10 to 100 times more populous than the NV center and thus can have stronger interactions, making them ideal for studying many-body physics."

But to tune their interactions, scientists need to be able to change the spin density, something that had previously seldom been achieved. With this new approach, Wang says, "We can tune the spin density so it provides a potential knob to actually tune such a system. That's the key novelty of our work."

Such a tunable system could provide more flexible ways of studying the quantum hydrodynamics, Wang says. More immediately, the new process can be applied to some existing nanoscale quantum-sensing devices as a way to improve their sensitivity.

Li, who holds a joint appointment in MIT's departments of Nuclear Science and Engineering and Materials Science and Engineering, explains that today's computers and information processing systems are all based on the control and detection of electrical charges, but some innovative devices are beginning to make use of the property called spin. The semiconductor company Intel, for example, has been experimenting with new kinds of transistors that couple spin and charge, potentially opening a path to devices based on spintronics.

"Traditional CMOS transistors use a lot of energy," Li says, "but if you use spin, as in this Intel design, then you can reduce the energy consumption by a lot." The company has also developed solid-state spin qubit devices for quantum computing, and "spin is something people want to control in solids because it's more energy efficient, and it's also a carrier of quantum information."

In the study by Li and his colleagues, the newly achieved level of control over spin density allows each NV center to act like a kind of atomic-scale "radar" that can both sense and control the nearby spins. "We basically use a particular NV defect to sense the surrounding electronic and nuclear spins. This quantum sensor reveals the nearby spin environment and how that's affected dynamically by the charge flow, which in this case is pumped up by the laser," Li says.

This system makes it possible to dynamically change the spin concentration by a factor of two, he says. This could ultimately lead to devices where a single point defect or a single atom could be the basic computational unit. "In the long run, a single point defect, and the localized spin and the localized charge on that single point defect, can be a computing logic. It can be a qubit, it can be a memory, it can be a sensor," he says.

He adds that much work remains to develop this newly found phenomenon. "We're not exactly there yet," he says, but what they have demonstrated so far shows that they have "really pushed down the measurement and control of the spin and charge state of point defects to an unprecedented level. So, in the long run, I think this would support using individual defect, or a small number of defects, to become the information processing and sensing devices."

In this work so far, Wang says, "we find this phenomenon and we demonstrate it," but further work is needed to fully understand the physical mechanism of what is taking place in these systems. "Our next step is to dig more deeply into the physics, so we would like to know better what's the underlying physical mechanism" behind the effects they see.

In the long term, "with better understanding of these systems, we hope to explore more quantum simulation and sensing ideas, such as simulating interesting quantum hydrodynamics, and even transporting quantum information between different spin defects."

The findings were made possible, in part, by the team's development of a new wide-field imaging setup that allows them to measure many different spatial locations within the crystalline material simultaneously, using a fast single-photon detector array, combined with a microscope. "We are able to spatially image the density distribution over different spin species like a fingerprint, and the charge transport dynamics," although that work is still preliminary, Wang says.

Although their work was done using lab-grown diamond, the principles could be applied to other crystalline solid-state defects, he says. NV centers in diamond have been attractive for research because they can be used at room temperature and they have already been well-studied. But silicon vacancy centers, donors in silicon, rare-earth ions in solids, and other crystal materials may have different properties that could turn out to be useful for particular kinds of applications.

"As information science progresses, eventually people will be able to control the positions and the charge of individual atoms and defects. That's the long-term vision," Li says. "If you can have every atom storing different information, it's a much larger information storage and processing capability" compared to existing systems where even a single bit is stored by a magnetic domain of many atoms. "You can say it's the ultimate limit of Moore's Law: eventually going down to one defect or one atom."

While some applications may require much more research to develop to a practical level, for some kinds of quantum sensing systems, the new insights can be quickly translated into real-world uses, Wang says. "We can immediately improve the quantum sensors' performance based on our results," he says.

"Overall, this result is very exciting for the field of solid-state spin defects," says Chong Zu, an assistant professor of physics at Washington University in St. Louis, who specializes in quantum information but was not involved in this work. "In particular, it introduces a powerful approach of using charge ionization dynamics to continuously tune the local spin defect density, which is important in the context of applications of NV centers for quantum simulation and sensing."

More information: Guoqing Wang et al, Manipulating solid-state spin concentration through charge transport, *Proceedings of the National Academy of Sciences* (2023). DOI: 10.1073/pnas.2305621120

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