The Great Potential of Diamond in Basic Science

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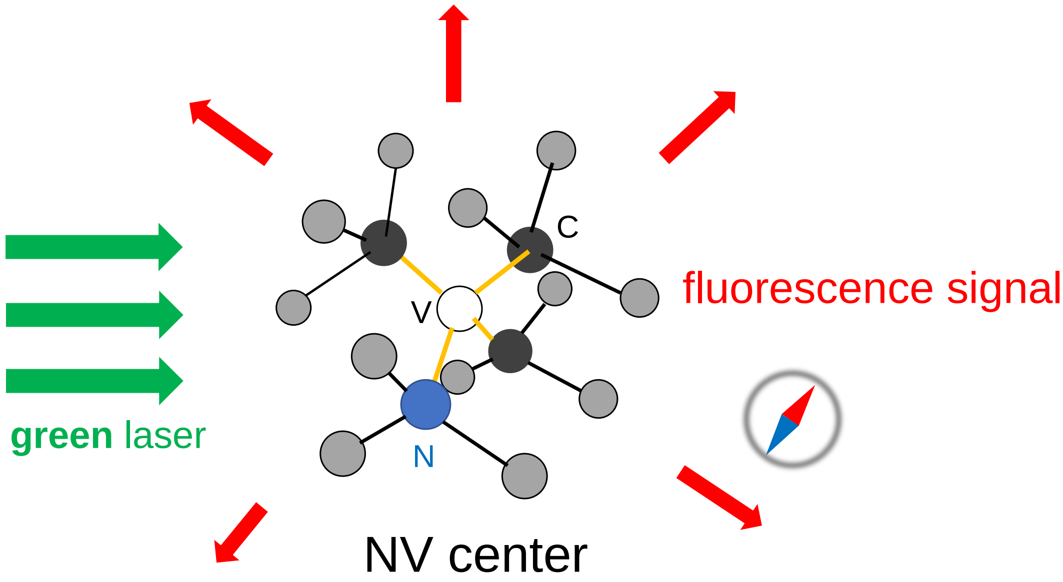

Diamonds are known for their strength and beauty. Many people favor this gemstone as an engagement ring or a wedding band. However, you may not know much about quantum technology using diamonds.

Pure diamonds are usually transparent to visible light. But if they include defects called color centers, they can get a color. The nitrogen-vacancy color center (NV color center or NV center) is one of them, giving a pink color to diamonds. The NV center is a point defect where one carbon atom in the diamond's crystal lattice is replaced by a nitrogen atom (N), leaving an adjacent lattice site empty (vacancy, V) (See Figure). To introduce NV centers into the diamond lattice, first, a small amount of nitrogen (N) is added during diamond synthesis. Then, vacancies (V) are introduced by electron or ion irradiation, followed by annealing of the diamond to form NV centers [1]. The NV center is known to emit a red fluorescence signal when illuminated with green light. Although the finding of the NV center goes back half a century, its potential has recently been rediscovered.

The trigger of the recent work was the observation of the electron spin of a single NV center using microscopy techniques in 1997 [2]. The NV center exhibits a magnetic property called spin. Spin is a fundamental entity in quantum mechanics describing the microscopic world. Usually, the nature of quantum degrees of freedom does not appear unless the system is isolated from the environment at ultra-low temperatures. However, it was found that the NV center has the unique property of exhibiting quantum behavior even at room temperature. This is because the diamond has strong interatomic bonding, and its spins are not easily perturbed. Therefore, research on quantum manipulation has been actively conducted to control and utilize the quantum behavior of electron spins in such NV centers [3] [4].

The study of quantum manipulation can lead to the realization of quantum computing. Quantum computing is the computation that takes advantage of quantum nature to attack the areas difficult to approach with classical computers. Quantum computers will have industrial applications in the future in various fields such as material science, chemistry, pharmaceuticals, and so on. However, there are many challenges in realizing a quantum computer that can withstand practical use. Current mainstream quantum computers typically require an ultra-low temperature environment to maintain quantum nature. Besides, they can only retain quantum states for a short time. The NV center is probably essential for quantum computers to approach practical use. The NV center can be used as the memory of quantum information because it can retain its quantum state for a long time. No need for a cryogenic environment requires extensive equipment.

The NV center has another application: quantum sensing. Quantum sensing is the use of a quantum system, quantum properties or quantum phenomena to measure a physical quantity [5]. A well-known example of quantum sensing is the use of the superconducting quantum interference device (SQUID) for the magnetometer. The SQUID can measure changes in the very weak magnetic field, by using the quantum property of the Josephson junction, which is a junction of a superconductor and an insulator. However, there are various restrictions on the use of the SQUID. One reason is that the macroscopic quantum state called the superconducting state can only exist stably at low temperatures and in low magnetic fields. Fortunately, the NV center has the potential to cover the weak areas of the SQUID. The NV center is extremely sensitive to changes in the surrounding environment like the magnetic field and temperature. This characteristic appears as a change in the energy level of the quantum state at the NV center, which can be detected by using microwaves. In this way, the NV center can be regarded as an atomic-sized single quantum spin sensor, as presented in 2008 [6] [7]. The NV center has multiple advantages over the SQUID. First, the operating temperature is up to 1000 K and there are few restrictions on temperature. Second, the technology to observe each electron spin in the NV center enables high spatial resolution at the nanometer level. Furthermore, an ensemble of NV centers allows imaging of the magnetic field from the luminescence distribution. This ease of imaging is a major attraction compared to the SQUID, which requires some ingenuity for high-resolution measurements. Research continues to be conducted to take advantage of the above advantages and the unique properties of the NV center.

Quantum sensing using the NV center will play an important role in basic science. For example, the NV center will act as a "nano quantum sensor" for the precise measurement of life phenomena. Conventional quantum sensors are limited in size and can only measure large structures in a cell. However, it is critical to measure changes in smaller proteins and other molecules to gain a deeper understanding of biological reactions in a cell. The NV center is the promising minuscule quantum sensor for this purpose. For example, by measuring precisely within cells at the NV Center, it may be possible to capture the changes taking place between normal cells becoming cancer cells. It enables a better understanding of the mechanism of cancer development!

The NV center will have industrial applications as well as basic science. The NV center can be applied to systems that monitor the current and temperature of batteries and power devices. Using highly sensitive quantum sensors allows for a wider range of measurements and provides more information. Placing this system in a car, for example, it will enable more efficient energy use and realize an environmentally friendly society.

As we have seen, there are many possible applications for the NV center. However, these must be just the beginning of the exploration of the possibilities, given the outstanding property of the NV center. I believe it can be the "Hidden Gems of Basic Science".

Reference

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