JOURNAL OF NANO- AND ELECTRONIC PHYSICS
Vol. **15** No 4, 04007(5pp) (2023)

ЖУРНАЛ НАНО- ТА ЕЛЕКТРОННОЇ ФІЗИКИ
Том **15** № 4, 04007(5сс) (2023)

Investigation of Novel Processes in the Physics of Condensed Matter: Recent Advances and Applications

P. William[1], G.S. Chhabra[2,*], Abha Choubey[3], Siddhartha Choubey[3], S. Yuvaraj[4]

[1] *Department of Information Technology, Sanjivani College of Engineering, SPPU, Pune, India*
[2] *Department of CSE, GITAM School of Technology, GITAM University, Visakhapatnam, India*
[3] *Department of Computer Science and Engineering, Shri Shankaracharya Technical Campus, CSVTU, Bhilai, India*
[4] *Department of Electronics & Communication, SRM College of Engineering &Technology, Chennai, India*

(Received 05 June 2023; revised manuscript received 17 August 2023; published online 30 August 2023)

The exploration of innovative condensed matter physics techniques, as well as their most current innovations and N2-V magnetometry scenarios, are covered in this paper. Nitrogen-vacancy (N2-V) cores in diamond are incorporated in the N2-V magnetometry method, which allows for highly sensitive and precise measurements of magnetic fields (B). With a particular emphasis on three areas such as ferromagnetic materials/Anti ferromagnetic materials, Superconducting materials and Metals/Semiconductors. We highlight the rapidly expanding interest in employing N2-V magnetometry to investigate condensed matter physics in this study. The behavior of specific magnetic domains, domain barriers, and other nanoscale structures could be studied using the high sensitivity and spatial resolution of N2-V magnetometry. The utilization of N2-V magnetometry in numerous disciplines, including biology and materials science, are additionally explored. Future applications of N2-V magnetometry in the study of innovative condensed matter physics processes provide a wealth of fascinating possibilities which includes the creation of novel diamond materials, the integration of N2-V magnetometry with other methodologies.

Keywords: Condensed matter, Nitrogen-vacancy (N2-V), Magnetic field, Nano science, Ferromagnetic materials, Anti ferromagnetic materials, Semiconductors.

DOI: 10.21272/jnep.15(4).04007 PACS numbers: 75.50.Ee, 75.50.Cc

1. INTRODUCTION

In physics, the term "novel processes" refers to novel and previously unrecognized occurrences or behaviors that take place in physical systems. These processes might have something to do with fundamental particles, how they interact, or how materials behave. Understanding the fundamental mechanics of the natural world requires research into novel physics processes, which can also result in the creation of new technologies and applications. Quantum entanglement, high-energy particle collisions, dark matter, topological materials, and quantum computing are a few examples of novel physics processes. Researching innovative physics processes is essential for expanding our knowledge of nature and can result in a variety of useful applications and technological improvements.

Condensed matter (CM) was a state of matter that develops when a great deal of atoms, molecules, or electrons join together and interact with one another to produce a solid or liquid. The study of these materials' electrical, magnetic, thermal, and optical properties as well as other physical characteristics is known as CM physics [1]. Metals, semiconductors, superconductors, polymers, and biological materials are just a few of the diverse types of materials that fall under the purview of CM physics [2]. The field was quite broad and encompasses a wide range of topics, including topological materials, optical properties of materials, thermal properties of materials, mechanical properties of materials, and electronic properties of materials. CM physics was a crucial field of study that has produced numerous technological advances, such as the creation of novel materials for electronics, energy storage, and other uses [3]. Studying the behavior of electrons within materials, including their interactions with other particles and their movement in reaction to applied fields, allows scientists to better understand phenomena like electrical conductivity, magnetism, and superconductivity [4]. The study of a material's thermal conductivity, specific heat, phase transitions, and other low-temperature critical events are all included in the research of a material's thermal characteristics. Studying a material's mechanical characteristics, including their elasticity, strength, and deformation patterns under stress, is known as mechanical property analysis [5].

A new family of materials called topological materials have distinctive electrical properties that are shielded by their topology [6]. For the creation of new electronic and computational technologies, research into these materials is crucial [7]. Quantum materials are substances that, on a macroscopic level, display quantum mechanical characteristics like superposition and entanglement. For the development of quantum computers, quantum sensors, and other technologies, research into these materials is crucial [8].

---

[*] gschhabra84@gmail.com

The results were presented at the 3rd International Conference on Innovative Research in Renewable Energy Technologies (IRRET-2023)

The study of using an electron's spin rather than its charge to store and process information is known as spintronics. For the creation of novel electronic devices, such as spin-based transistors and memory, spintronic research is crucial [9]. The behavior of materials that are not in thermodynamic equilibrium is referred to as non-equilibrium phenomena. Understanding the dynamics of complex systems, such as glasses and polymers, requires research into these phenomena. Topological phases of matter, such as topological insulators, which have special electronic properties that are protected by their topology, are examples of phases of matter with topological features [10].

This paper discusses the principles, sensitivity, and spatial resolution of N2-V magnetometry in section 2 along with its applications in studying spin textures, magnetic excitations in Section 3, and the properties of superconductors in section 4, metals and semiconductors in section 5. The paper also explores the use of N2-V magnetometry in AFM/FM materials evaluation and concludes by highlighting the potential of N2-V magnetometry as a powerful tool for studying magnetic materials at the nanoscale in section 6.

2. N2-V MAGNETOMETRY PRINCIPLES

In the model, Marangoni convection, recoil pressure and surface tension were used as unique interface captured techniques. Considering that surface tension is a million times more powerful than gravity, it was found that fused powders might create a continuous cladding layer under its influence rather than gravity [11].

Nitrogen-vacancy (N2-V) centers in diamond are used as the sensing component in N2-V magnetometry [12]. The measuring of the spin state of the N2-V centers in response to Magnetic Field (B) is one of the fundamental tenets of N2-V magnetometry. The nitrogen atom and vacancy (a carbon atom lacking) in the diamond lattice make up the N2-V centers [13]. The N2-V centers can function as B sensors due to their electronic spin states' sensitivity to B. Laser light and fluorescence detection can be used to control and measure the N2-V centers' spin states [14]. The N2-V magnetometry concepts entail monitoring variations in the N2-V centers' fluorescence in response to B. It may be measured with extremely high sensitivity and spatial resolution using N2-V-magnetometers [15]. They are very helpful for capturing nanoscale B images, such as those seen in biological systems or magnetic data storage devices. They can also be used to gauge a molecule's or nanoparticle's magnetic characteristics [16,17]. The N2-V magnetometry method relies on the electronic spin states of diamond N2-V centers to identify and quantify B. Numerous fields, including biology, magnetic data storage, and materials research, could benefit from the use of this technique [18, 19].

2.1 N2-V Magnetometry's Sensitivity

The extreme sensitivity of N2-V magnetometry, which makes it a useful instrument for determining B at the nanoscale, is well recognized [20]. The characteristics of the diamond sample, the stimulation intensity and duration, and the detecting technique all affect the N2-V magnetometry's sensitivity. It is possible to measure both dc and ac magnetic responses using the N2-V center, by implementing various magnetic-sensing methods. One equation generalizes the NV dc and ac magnetometry's sensitivity. It includes the following four contributions: overhead time, readout, spin dephasing, and spin projection limit. A particular type of point defect in the diamond lattice is the N2-V center that shown in Fig. 1.

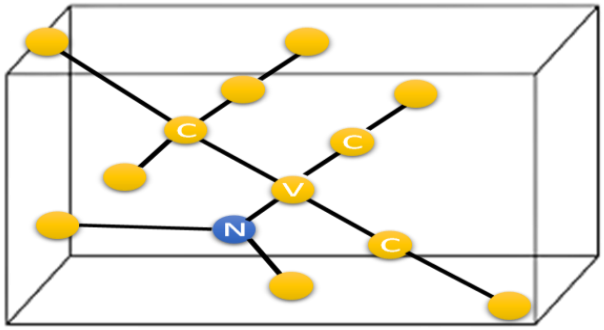

Fig. 1 – Nitrogen-Vacancy Center illustration and diamond lattice

$$\eta = \alpha \frac{1}{2\pi\gamma} \frac{1}{\sqrt{N\tau}} \frac{1}{e^{(\tau/T)p}} \sqrt{1+\frac{1}{C^2 n_{avg}}} \sqrt{\frac{t_j+\tau+t_R}{\tau}} \qquad (1)$$

Taylor et al. brought up the restricted sensitivity due to spin-projection.

Where, γ = Gyromagnetic ratio of electrons
N = number of NV centers in the ensemble
τ = free precession for each unit of measurement
α = Diff between ac and dc signals in terms of effective field value
α = 1 for (Dc Ramsey magnetometry), and $\alpha = \frac{\pi}{2}$ for (ideal Ac Hahn)

The obtainable sensitivity is nonetheless compromised by experimental nonidealities, spin dephasing such poor reading and overhead time. First, spin dephasing during precession reduces the sensitivity η for higher values of τ.

$$\frac{1}{e^{-(\tau/T)p}} \qquad (2)$$

Where, $T = T_2^*$
P = Stretched Exponential parameter

The spin bath encircling the N2-V center is related to P. Second, the spin projection limit, which is taken into account by the readout factor in Equation 1, significantly reduces sensitivity by prohibiting SSD of the NV spin state with the typical NV optical readout technique.

Third, when particular readout methods, like SCC or SRM methods, are used. Compared with interrogation period τ, t_I and t_R can be significant. The amount of time that is spent in spin precession can be used to measure this nonideality.

$$\sqrt{\frac{t_j+\tau+t_R}{\tau}} \qquad (3)$$

The diamond quality, the excitation power, the duration, the detection method, and the gradient of the B are some of the variables that affect the NV magnetometer's sensitivity.

The quality of the diamond sample affects N2-V magnetometry's sensitivity. Higher sensitivity may result from the diamond's higher purity and reduced flaw density. By raising the stimulation power and duration, which increases the number of N2-V centers that can be detected, the sensitivity of N2-V magnetometry can be enhanced. More sensitive detection techniques, including time-resolved detection or lock-in detection, can increase the NV magnetometer's sensitivity. The gradient of the B being measured affects the sensitivity of N2-V magnetometry. A greater gradient produces a greater sensitivity.

2.2 N2-V Magnetometry's Spatial Resolution

The spatial resolution of N2-V magnetometry depends on a number of variables, including the B gradient, size and density of the N2-V centers being measured, and the type of detection technique being utilized. A useful instrument for capturing B at the nanoscale is N2-V magnetometry, which has exhibited spatial resolutions in the nanometer range.

The excellent spatial resolution of N2-V magnetometry was one of its main benefits. An example of this is the realization of a spatial resolution of 10 nm utilizing scanning probe N2-V magnetometry. Sensitivity and spatial resolution, however, are always trade-offs. Since it is widely known that poor coherence qualities, or alternatively, shorter dephasing times T_2^* and T_2 occur close to the diamond surface (10 nm). Number of NV faults used in the investigation is another restriction. The best spatial resolution and coherence are provided by a single NV defect, but in comparison to ensemble detection, the sensitivity of the photon shot-noise-limited system would be significantly damaged.

From these factors in mind, Table 1 provides a summary of sensitivity and the spatial resolution currently accessible to the investigation of CM. In order to extend the spatial resolution of atomic force microscopy past the scanning probe technique and optical diffraction limit was either employed or putting a nano diamond. To attain a spatial resolution of 10 nm in both situations, the distance between the diamond surface and N2-V center should be about 10 nm or less. SRM techniques can be used to achieve N2-V magnetometry spatial resolution at the nanometer scale without the need for scanning probes.

3. AFM/FM MATERIALS EVALUATION

Probing AFM/FM materials involves measuring the magnetic and structural properties of materials that have both AFM (AFM) and ferromagnetic (FM) phases. These materials have unique magnetic and electronic properties that make them of interest for a range of applications, including spintronics and magnetic data storage.

Table 1 – Condensed Matter Systems Research: Typical Spatial Resolution and Sensitivity of N2-V Magnetometry

Types	Ac Magnetometry	Dc Magnetometry
Atomic Force Microscope	50-100 $nT/Hz^{1/2}$	3-10 $\mu T/Hz^{1/2}$
Confocal	4-100 $nT/Hz^{1/2}$	0.03-3 $\mu T/Hz^{1/2}$
Large Ensemble	1 $pT/Hz^{1/2}$	15 $T/Hz^{1/2}$

Some of the technique used to probe AFM/FM materials are as follows: X-ray diffraction, Scanning tunneling microscopy (STM), Magnetic force microscopy (MFM), Magnetometry, Scanning transmission electron microscopy (STEM), X-ray magnetic circular dichroism (XMCD) and Polarized neutron scattering. One method for figuring out a material's crystal structure is X-ray diffraction. This can reveal details on how the atoms are arranged in the substance, including where and how their magnetic moments are arranged. The technical advancements for the investigation of magnetic excitations and spin texturing will be covered in this subsection.

3.1 Spin Texture Features

Spin texture characterization refers to the process of quantitatively describing the distribution and orientation of electron spins in a material. It is an important area of research in CM physics, as it is essential for understanding the properties of materials with magnetic or spin-dependent behavior. Spin texture can be characterized by several features, including, Spin polarization, Spin density, Spin texture symmetry, Topological spin texture, and Magnetic ordering.

For the creation of new materials with specialized magnetic and spin-dependent behavior, an understanding of the characteristics of spin texture is essential. It is also crucial for creating new spintronics-based technologies that store and process information using the spin of electrons rather than their charge. Numerous methods, such as angle-resolved photoemission spin-polarized scanning tunneling microscopy (SP-STM), spectroscopy (ARPES), X-ray magnetic circular dichroism (XMCD), spin-resolved electron energy loss spectroscopy (SREELS), and magneto-optical Kerr effect (MOKE)can be used to determine the characteristics of the spin texture. These methods are crucial for comprehending the characteristics of materials with magnetic or spin-dependent behavior because they offer useful information on the distribution and orientation of electron spins in materials.

In an NV center-based diamond microscope, the sample of interest is put on a diamond nanocrystal that contains NV centers, and the NV centers are optically excited by a laser. A sensitive camera uses the light emitted by the NV centers to build an image of the sample with a resolution of a few nanometers. Applications for this kind of microscope include biological imaging, materials science, and quantum sensing. The NV center-based diamond microscope, for instance, can be utilized to examine individual cells or even subcellular structures with high spatial resolution in biological imaging which shown in Fig. 2.

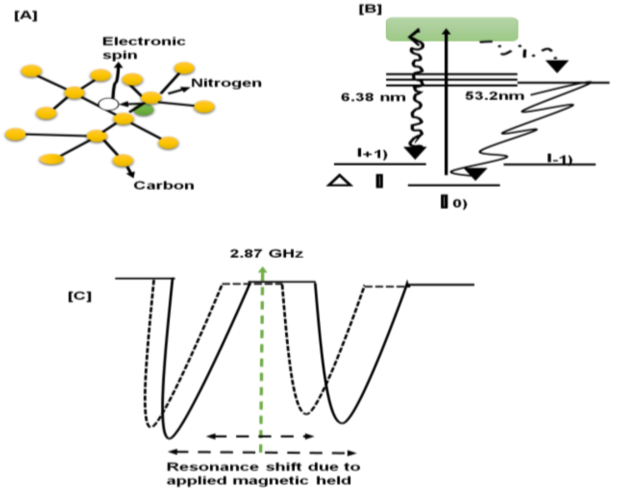

Fig. 2 – High spatial resolution in biological imaging with subcellular structure

3.2 Magnetic Excitations

Through neutron scattering studies, magnetic excitations, which are the collective behavior of magnetic moments in a material, can be seen. Unpaired electrons with spin are found in atoms or ions within the material, which causes these magnetic moments to form. Numerous magnetic phenomena, including ferromagnetism, antiferromagnetism, and paramagnetism, can result from the interactions between these magnetic moments.

In materials research and CM physics, N2-V magnetometry has a wide range of potential applications. N2-V magnetometry, for instance, can be used to examine the magnetic characteristics of novel substances like topological insulators or magnetic skyrmions. The behavior of magnetic materials under severe circumstances, such as high temperatures or strong B, can also be studied using N2-V magnetometry. Along with coherent transport of spin waves, unique magnon condensate produced by the interactions of magnons has garnered a lot of interest in recent years.

4. EXAMINING SUPERCONDUCTORS

At low temperatures, superconductors are substances that can conduct electricity with no resistance. Many fascinating phenomena, including topological superconductivity and high-temperature superconductivity, have been discovered as a result of decades of active research in the field of superconductivity. It has become clear that N2-V magnetometry is an effective instrument for researching superconductors. It can be used, for example, to find a B generated by superconducting vortices. A lattice of vortices, or areas where the superconducting current flows in a circular pattern, can form when a superconductor is exposed to a B. The N2-V center in a diamond substrate can pick up B created by the vortices.

N2-V magnetometry can be used to detect the magnetic characteristics of a superconductor as well as map out the distribution of vortices within it. N2-V magnetometry, for instance, can be used to gauge the dimensions, densities, and movements of vortices. The behavior of superconductors in various situations, such as at various temperatures or in the presence of external B, can be understood using this information. The study of superconductivity at high pressure is another novel application of NV sensors. Type 1 superconductors are made of basic materials, have a small critical magnetic field, complete Meissner effect, and a limited temperature range. Type 2 superconductors are made of complex materials with a higher capacity to trap magnetic flux and have high critical magnetic fields, partial Meissner effects, a wider temperature range, and partial Meissner effects.

These findings show that nanoscale B imaging using scanning probe N2-V magnetometry is an effective method for studying intricate electrical systems.

5. CONCLUSION

In this review, we have covered how N2-V magnetometry can be used to examine CM materials. The right sensors with the high B sensitivity and high spatial resolution needed to assess materials in various working environments are N2-V centers, because they are point-like defects with exceptional coherent features in diamond. In the study of spin texturing, magnetic excitation, and the non-invasive characterization of electron transport, N2-V magnetometry has developed into a flexible and potent technique. N2-V magnetometry has been a potent tool for analyzing innovative CM physics phenomena in recent years. In the study of novel processes in the physics of CM, N2-V magnetometry has made a substantial contribution and opened up new directions for study. It is expected that N2-V magnetometry will continue to play a significant role in the development of new materials with novel properties as well as in our understanding of CM physics with continued advancements in this technology. Future applications of N2-V magnetometry in the study of innovative CM physics processes provide a wealth of fascinating possibilities. These include the creation of novel diamond materials, the integration of N2-V magnetometry with other methodologies, the study of unusual or difficult materials, and the nanoscale analysis of magnetic materials. The development of new materials with unique features and several new insights into the behavior of materials are predicted to result from continued improvements in this technology.

REFERENCES

1. M. Zheng, L. Wei, J. Chen, Q. Zhang, C. Zhong, X. Lin, W. Huang, *Int. J. Heat Mass Transfer* **140**, 1091 (2019).
2. S.F. Azha, L. Sellaoui, M.S. Shamsudin, S. Ismail, A. Bonilla-Petriciolet, A.B. Lamine, A. Erto, *Chem. Eng. J.* **351**, 221 (2018).
3. B.J. Reddy, P. Vickraman, A.S. Justin, *Appl. Phys. A* **124**, 409 (2018).
4. Q. Zhang, Q. Li, T.M. Young, D.P. Harper, S. Wang, *ACS Sustain. Chem. Eng.* **7** No 9, 8706 (2019).
5. Y. Wang, X. Liu, A. Kraslawski, J. Gao, P. Cui, *J. Cleaner Production* **213**, 480 (2019).
6. L. Guo, P. Liang, *New J. Phys.* **22** No 7, 075003 (2020).
7. A.I. Jewett, D. Stelter, J. Lambert, S.M. Saladi, O.M. Roscioni, M. Ricci, L. Autin, M. Maritan, S.M. Bashusqeh, T. Keyes, R.T. Dame, *J. Molecular Biol.* **433** No 11, 166841 (2021).
8. D.M. Kennes, M. Claassen, L. Xian, A. Georges, A.J. Millis, J. Hone, C.R. Dean, D.N. Basov, A.N. Pasupathy, A. Rubio, *Nat. Phys.* **17** No 2, 155 (2021).
9. A.T. Sahlol, M. Abd Elaziz, A. Tariq Jamal, R. Damaševičius, O. Farouk Hassan, *Symmetry* **12** No 7, 1146 (2020).
10. X. Tang, L. Kou, *J. Phys. Chem. Lett.* **10** No 21, 6634 (2019).
11. J. Han, X. An, *J. Dispers. Sci. Technol.* **41** No 1, 30 (2020).
12. J. Li, J. Lu, A. Chew, S. Han, J. Li, Y. Wu, H. Wang, S. Ghimire, Z. Chang, *Nat. Commun.* **11** No 1, 2748 (2020).
13. A.R. McCray, T. Cote, Y. Li, A.K. Petford-Long, C. Phatak, *Phys. Rev. Appl.* **15** No 4, 044025 (2021).
14. X. Yu, *J. Magn. Magn. Mater.* **539**, 168332 (2021).
15. J.F. Barry, J.M. Schloss, E. Bauch, M.J. Turner, C.A. Hart, L.M. Pham, R.L. Walsworth, *Rev. Modern Phys.* **92** No 1, 015004 (2020).
16. L. Xinyu, Z. Doudou, Z. Junzhi, W. Qimeng, L. Yankang, G. Hao, T. Jun, S. Yasuhiro, L. Yanjun, M. Zongmin, L. Jun, *Sensor. Actuat. A: Phys.* **352**, 114206 (2023).
17. J. Zhang, L. Xu, G. Bian, P. Fan, M. Li, W. Liu, H. Yuan, *arXiv preprint* arXiv:2010.10231 (2020).
18. Y. Li, F.A. Gerritsma, S. Kurdi, N. Codreanu, S. Gröblacher, R. Hanson, R. Norte, T. van der Sar, *ACS Photon.* **10** No 6, 1859 (2023).
19. A. Kuwahata, T. Kitaizumi, K. Saichi, T. Sato, R. Igarashi, T. Ohshima, Y. Masuyama, T. Iwasaki, M. Hatano, F. Jelezko, M. Kusakabe, *Sci. Rep.* **10** No 1, 2483 (2020).
20. F.M. Stürner, Y. Liu, P.O. Colard, M. Markham, F. Jelezko, *Appl. Phys. Lett.* **119** No 13, 134001 (2021).

Нові процеси у фізиці конденсованого середовища: останні досягнення та застосування

P. William[1], G.S. Chhabra[2], Abha Choubey[3], Siddhartha Choubey[3], S. Yuvaraj[4]

[1] *Department of Information Technology, Sanjivani College of Engineering, SPPU, Pune, India*
[2] *Department of CSE, GITAM School of Technology, GITAM University, Visakhapatnam, India*
[3] *Department of Computer Science and Engineering, Shri Shankaracharya Technical Campus, CSVTU, Bhilai, India*
[4] *Department of Electronics & Communication, SRM College of Engineering &Technology, Chennai, India*

В даній роботі розглянуті результати досліджень інноваційних методів фізики конденсованого стану, а також інновації та сучасні сценарії магнітометрії N2-V. Ядра з вакансіями азоту (N2-V) в алмазі включені в метод магнітометрії N2-V, який дозволяє проводити високочутливі та точні вимірювання магнітних полів (B). Особливий акцент на трьох групах матеріалів, таких як феромагнітні метали/антиферомагнітні метали, надпровідні матеріали та метали/напівпровідники. У цьому дослідженні ми підкреслюємо стрімко зростаючий інтерес до використання магнітометрії N2-V для дослідження фізики конденсованих речовин. Поведінку конкретних магнітних доменів, доменних бар'єрів та інших нанорозмірних структур можна вивчати за допомогою високої чутливості та просторової роздільної здатності магнітометрії N2-V, додатково досліджується її використання в різних галузях, включаючи біологію та матеріалознавство. Майбутнє застосування магнітометрії N2-V у вивченні інноваційних процесів фізики конденсованого стану надає багато можливостей, включаючи формування нових алмазних матеріалів та інтеграцію даного методу з іншими.

Ключові слова: Конденсована речовина, Вакансія азоту (N2-V), Магнітне поле, Нанонаука, Феромагнітні матеріали, Антиферомагнітні матеріали.