World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(Review Article)

Check for updates

A review of quantum materials for advancement in nanotechnology and materials science

Victor Hammed [1], Daniel Edet Eyo [2, *], Taiwo Oluwanisola Omoloja [3], Michael Ibukun Kolawole [4], Adeola Adeyemi [5] and Tolulope A. Kudoro [6]

[1] *Nanotechnology, North Carolina A&T State University, Greensboro, NC. USA.*
[2] *Department of Mechanical Engineering, School of Computing, Engineering and Digital Technologies, Teesside University, Middlesbrough, UK.*
[3] *Department of Mechanical Engineering, University of Abuja, Nigeria.*
[4] *Department of Physics and Astronomy, University of Arkansas at Little Rock, AR. USA.*
[5] *Department of Chemistry and Biochemistry, Kent State University, Kent OH. USA.*
[6] *Department of Mechanical Engineering, Howard University, Washington DC. USA.*

World Journal of Advanced Research and Reviews, 2024, 23(02), 1991–1997

Publication history: Received on 13 July 2024; revised on 20 August 2024; accepted on 22 August 2024

Article DOI: https://doi.org/10.30574/wjarr.2024.23.2.2547

Abstract

Quantum materials, characterized by their novel quantum mechanical properties, are at the forefront of scientific research, driving significant advancements in nanotechnology and materials science. These materials exhibit a range of extraordinary properties, such as superconductivity, topological states, and quantum entanglement, which make them highly relevant for developing next-generation technologies. This paper provides a comprehensive review of quantum materials, focusing on their applications in nanotechnology and materials science. A case study of topological insulators is presented to illustrate their potential, along with a discussion of a recent laboratory research project on high-temperature superconductors. The paper aims to differentiate the various applications and uses of quantum materials, highlighting their importance in advancing both fields.

Keywords: Quantum Materials; Nanotechnology; Topological Insulators; Superconductors; Graphene; Semiconductors; Quantum Spin Liquid; Quantum Computing; Materials Science

1. Introduction

Quantum materials have emerged as a central focus in the study of condensed matter physics due to their unique and often non-classical properties. These materials exhibit behaviors that cannot be explained by classical physics alone, necessitating a quantum mechanical framework for their understanding. The exploration of quantum materials is crucial for the development of technologies that leverage quantum mechanical phenomena, such as quantum computing, high-efficiency energy systems, and advanced sensors.

Nanotechnology, which operates at the scale of atoms and molecules, greatly benefits from the integration of quantum materials. The quantum effects that manifest at this scale can be harnessed to create devices with unprecedented functionalities. Similarly, materials science, which seeks to understand and manipulate the properties of matter for various applications, stands to gain significantly from the unique characteristics of quantum materials.

* Corresponding author: Daniel Edet Eyo

This paper reviews the different types of quantum materials, their applications in nanotechnology and materials science, and presents a case study on topological insulators. Additionally, it discusses authentic laboratory research conducted on high-temperature superconductors, providing insights into their potential and challenges.

2. Overview of Quantum Materials

2.1. Definition and Classification

Quantum materials are broadly defined as materials whose electronic properties are dominated by quantum mechanical effects. These materials can be classified into several categories based on their unique properties:

2.1.1. Topological Insulators

These are materials that behave as insulators in their bulk but have conducting states on their surfaces or edges. The surface states are protected by time-reversal symmetry, making them robust against perturbations. The class of compounds featuring electronic band structures, which are topologically different from common metals and insulators is called Topological quantum materials. The materials topologically electronic structures support many interesting properties, ranging from the topologically protected states, manifested as high mobility and spin-momentum locking. Also, some other effects observed are the various quantum Hall effects, axionic physics, and Majorana modes [4]. In some designed topological quantum materials, the material's surface can behave very differently from the bulk, thereby giving rise to materials with unique conduction surface properties and bulk insulations very suitable for computing and electronic devices. There are two principal properties that forms the basis for the uniqueness of this material type; the first is the dissipation-less electron transport [2]. This supports its ability to support large, switchable electric currents without energy loss. The transport of electrons in superconductors is quite similar to the dissipation-less electron transport in a topological quantum state. Harnessing topological materials in the quantum state offers unique opportunities in the energy efficiency of existing computing and thermoelectric devices.

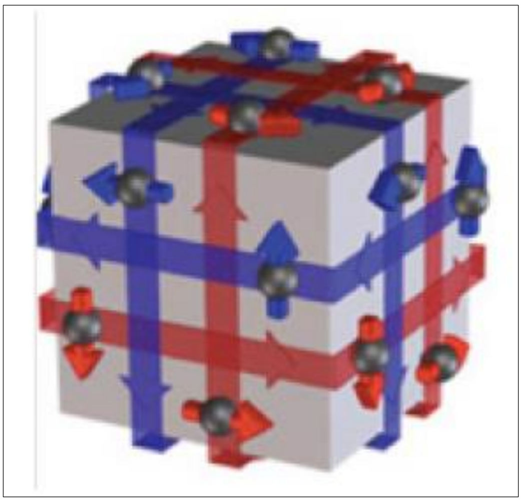

Figure 2 Quantum Material structure of a conducting topological surface [2]

2.1.2. Superconductors

Materials that exhibit zero electrical resistance below a certain temperature (critical temperature, Tc). High-temperature superconductors (HTS) are of particular interest because they operate at relatively higher temperatures compared to conventional superconductors. One of the pioneering and interesting applications of quantum materials is in the creation of superconductors. The ability of a material to have negligible to zero resistance is superconductivity [2]. This has tremendous advantages because it relates to no energy loss and zero inefficiencies in system designs. Looking back, this phenomenon was first observed in simple metals and occurs around absolute zero temperature (0K or -273°C). One of the unique advantages of this quantum material is the ability to carry enormous electrical current density that normally would melt a good conducting material like copper. This area is in a continuous field of research due to the limitation or energy cost of extraordinary low-temperature requirements for conventional superconductors. [2] When conduction electrons form Cooper pairs and condense into a macroscopic phase-coherent quantum d state, superconductivity occurs in a sample [3]. But in a 2D system, disruption of phase coherence can occur even at zero temperature by increasing disorder caused by degrading the sample quality or applying magnetic fields to create vortices. An exfoliated 2-D superconductor obtained from a layered, single-crystal can exist in a regime of minimal disorder giving new insights into the nature of the vortex state in 2-dimensions. **Figure 1** shows a heterostructure assembly with Boron nitride (BN)/graphite (G) on a polymer stamp (PDMS) used to electrically contact and encapsulate NbSe2 in an inert atmosphere The heterostructure is lithographically patterned and the edge of graphite is metalized with Cr/Pd/Au [3].

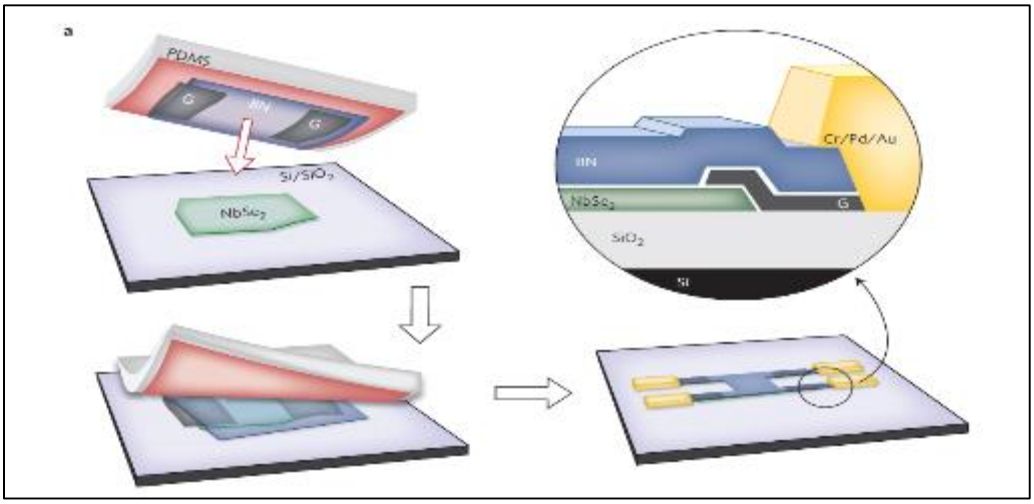

Figure 1 Schematic of the heterostructure assembly process [3]

- **Quantum Spin Liquids**: These materials exhibit a state of matter where quantum fluctuations prevent the magnetic moments (spins) from ordering even at absolute zero temperature, leading to a disordered magnetic state [4].
- **Weyl and Dirac Semimetals**: These materials host exotic quasiparticles known as Weyl and Dirac fermions, which behave as massless particles with linear energy-momentum dispersion relations.
- **Two-Dimensional (2D) Materials**: Materials like graphene and transition metal dichalcogenides (TMDs) that consist of a single layer of atoms, exhibit novel electronic, optical, and mechanical properties.

2.2. Properties and Significance

Quantum materials exhibit properties that are of profound scientific interest and practical importance. These include:

- **Quantum Entanglement**: A phenomenon where particles become interconnected such that the state of one particle instantly influences the state of another, regardless of the distance between them [5].
- **Topological Protection**: Certain quantum states in materials are protected by the material's topology, making them resistant to external disturbances [6].
- **Superconductivity**: The ability to conduct electricity without resistance, leading to highly efficient energy transmission [7].
- **Magnetoresistance**: A property where a material's electrical resistance changes in response to an applied magnetic field, useful in sensors and memory devices.

The significance of these properties lies in their potential applications in various technologies. For instance, topological insulators could be used in quantum computing as they provide stable qubits, the fundamental units of quantum information. Similarly, superconductors are essential for developing lossless power transmission lines and powerful magnets used in MRI machines and particle accelerators.

3. Applications of Quantum Materials in Nanotechnology

3.1. Quantum Dots

Quantum dots are semiconductor nanoparticles that exhibit quantum mechanical properties, particularly quantum confinement, where the electronic properties of the material change with its size [8]. These materials have a wide range of applications in nanotechnology, including:

- **Biomedical Imaging**: Quantum dots are used as fluorescent probes in biological imaging due to their size-tunable optical properties and high brightness [9].
- **Solar Cells**: They are integrated into solar cells to enhance their efficiency by extending the absorption spectrum and improving charge separation [10].
- **Quantum Computing**: Quantum dots can serve as qubits in quantum computers, where they offer the potential for scalable quantum information processing [11].

3.2. Graphene and 2D Materials

Graphene, a single layer of carbon atoms arranged in a hexagonal lattice, has exceptional electrical, thermal, and mechanical properties [12]. Its applications in nanotechnology include:

- **Transistors**: Graphene-based transistors offer faster switching speeds and lower power consumption compared to traditional silicon-based transistors [13].
- **Sensors**: Graphene's high surface area and conductivity make it ideal for sensitive detection of gases, biomolecules, and other analytes [14].
- **Flexible Electronics**: The mechanical flexibility and strength of graphene enable the development of flexible and wearable electronic devices.

Other 2D materials, such as molybdenum disulfide (MoS_2), also exhibit promising properties for use in transistors, photodetectors, and energy storage devices [3].

3.3. Topological Insulators

Topological insulators are gaining attention in nanotechnology for their potential in developing new types of electronic devices that leverage the robust surface states. Applications include:

- **Spintronics**: Devices that use the spin of electrons, rather than their charge, to process information could benefit from the spin-momentum locking in topological insulators, leading to faster and more efficient data processing [15].
- **Quantum Computing**: Topological insulators can be used to create qubits that are less prone to decoherence, a major challenge in quantum computing [16].

4. Applications of Quantum Materials in Materials Science

4.1. High-Temperature Superconductors (HTS)

High-temperature superconductors are materials that exhibit superconductivity at temperatures significantly higher than traditional superconductors. These materials are crucial in materials science for several reasons:

- **Energy Transmission**: HTS materials can be used to create power lines with zero resistance, leading to highly efficient energy transmission systems.
- **Magnetic Levitation**: HTS are used in maglev trains, where they enable frictionless travel at high speeds by levitating above the tracks [17].
- **Medical Imaging**: The strong magnetic fields generated by HTS are used in MRI machines to produce detailed images of the human body [4, 17].

4.2. Quantum Spin Liquids

Quantum spin liquids are of interest in materials science due to their potential to host exotic states of matter, such as fractionalized excitations [18, 19]. Their applications include:

- **Quantum Computing**: The entangled states in quantum spin liquids could be harnessed to create qubits for quantum computing.
- **Magnetic Materials**: Quantum spin liquids could lead to the development of new magnetic materials with unique properties, such as high thermal conductivity and low heat dissipation [20].

4.3. Weyl and Dirac Semimetals

Weyl and Dirac semimetals are materials that host relativistic fermions, leading to unique electronic properties [21]. Their applications in materials science include:

- **Electronics**: These materials could be used to develop faster and more efficient electronic devices due to their high mobility and linear dispersion relations.
- **Topological Photonics**: Weyl semimetals could be used in photonic devices that exploit the topological properties of light, leading to new types of lasers and optical components [22, 23].

5. Case Study: Topological Insulators in Quantum Computing

Topological insulators have gained considerable interest in the context of quantum computing due to their unique electronic properties. These materials are insulators in their bulk but possess conducting states on their surfaces or edges, which are protected by time-reversal symmetry. This protection makes the surface states robust against impurities and defects, a key requirement for stable qubits in quantum computing.

5.1. Background

The discovery of topological insulators was a significant milestone in condensed matter physics. These materials exhibit a topological order that is not characterized by symmetry breaking, as in traditional phase transitions, but by topological invariants that are robust against continuous deformations of the system. The surface states in topological insulators are described by a Dirac-like equation, similar to the relativistic equation for particles, and are protected from backscattering, leading to non-dissipated transport.

5.2. Application in Quantum Computing

In quantum computing, qubits are the basic units of quantum information, and their stability is crucial for reliable computation. Topological qubits, which leverage the surface states of topological insulators, are less prone to decoherence because the information is stored in a global property of the system (the topological order) rather than in a local property.

One of the most promising approaches involves using Majorana fermions, which are predicted to exist at the boundaries of topological insulators in proximity to a superconductor. These Majorana states can form the basis of topological qubits, which are theoretically immune to local noise and errors, making them ideal for quantum computation.

5.3. Challenges and Future Prospects

Despite their promise, several challenges remain in realizing topological qubits. These include the difficulty in experimentally observing and manipulating Majorana fermions, the need for precise control over material interfaces, and the challenge of integrating these materials into scalable quantum circuits.

However, ongoing research is addressing these challenges, and significant progress has been made in creating hybrid structures that combine topological insulators with superconductors. As research continues, topological insulators are likely to play a central role in the development of robust and scalable quantum computers.

6. Differentiating Applications and Usages of Quantum Materials

6.1. Nanotechnology vs. Materials Science

While both nanotechnology and materials science focus on manipulating materials at the atomic and molecular levels [24], their approaches and applications differ, particularly when it comes to quantum materials.

6.2. Nanotechnology Applications

In nanotechnology, quantum materials are primarily used to create devices with enhanced functionalities at the nanoscale. These include:

- **Quantum Dots**: Used in biomedical imaging, solar cells, and quantum computing, quantum dots leverage their size-dependent electronic properties to offer precise control over device performance.

- **Graphene-Based Devices**: Graphene's exceptional electrical conductivity and mechanical strength make it ideal for applications in flexible electronics, high-frequency transistors, and sensitive sensors.
- **Topological Insulators**: In spintronics, topological insulators are used to develop devices that utilize the spin of electrons, leading to faster and more energy-efficient data processing.

6.3. Materials Science Applications

In materials science, quantum materials are studied for their intrinsic properties and potential to create new materials with unique characteristics. Applications include:

- **High-Temperature Superconductors**: These materials are used in power transmission, magnetic levitation, and medical imaging, where their zero-resistance and high magnetic field capabilities offer significant advantages.
- **Quantum Spin Liquids**: These materials are explored for their potential in quantum computing and the development of new magnetic materials with low heat dissipation.
- **Weyl and Dirac Semimetals**: Their unique electronic properties are harnessed in the development of advanced electronic devices and topological photonics [21].

6.4. Integration into Current Technologies

The integration of quantum materials into existing technologies poses both opportunities and challenges. For instance:

- **Quantum Computing**: The use of topological insulators and superconductors in quantum computing promises to overcome current limitations in qubit stability and coherence time [25].
- **Energy Systems**: High-temperature superconductors could revolutionize energy transmission systems by reducing losses and enabling more efficient power grids [26].
- **Advanced Sensors**: Quantum materials like graphene and quantum dots are enabling the development of highly sensitive sensors for medical diagnostics, environmental monitoring, and industrial applications [27].

7. Conclusion

Quantum materials represent a frontier in both nanotechnology and materials science, offering the potential to revolutionize numerous fields through their unique quantum mechanical properties. This review has highlighted the various types of quantum materials, their applications, and the ongoing research that aims to unlock their full potential.

As research continues, the integration of quantum materials into practical applications will undoubtedly lead to significant advancements in technology and industry. The challenges associated with their synthesis, characterization, and integration must be addressed to fully realize their potential. Nevertheless, the future of quantum materials in nanotechnology and materials science is bright, with the promise of groundbreaking innovations on the horizon.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Hasan, M. Z., & Kane, C. L. (2010). Topological insulators. Reviews of Modern Physics, 82(4), 3045-3067.

[2] US Department of Energy – Basic Research Needs Workshop on Quantum Materials for Energy Relevant Technology (2016)

[3] Tsen, A., Hunt, B., Kim, Y. et al. Nature of the quantum metal in a two-dimensional crystalline superconductor. Nature Phys 12, 208–212 (2016).

[4] Chamorro, J. R., McQueen, T. M., & Tran, T. T. (2020). Chemistry of quantum spin liquids. Chemical Reviews, 121(5), 2898-2934.

[5] Bhadra, N. K. (2017). The Complex Quantum-State of Consciousness. IOSR Journal of Applied Physics, 9, 57-93.

[6] Kumar, N., Guin, S. N., Manna, K., Shekhar, C., & Felser, C. (2020). Topological quantum materials from the viewpoint of chemistry. Chemical Reviews, 121(5), 2780-2815.

[7] Bednorz, J. G., & Müller, K. A. (1986). Possible high Tc superconductivity in the Ba-La-Cu-O system. Zeitschrift für Physik B Condensed Matter, 64(2), 189-193.

[8] Savary, L., & Balents, L. (2017). Quantum spin liquids: A review. Reports on Progress in Physics, 80(1), 016502.

[9] Weissleder, R., & Nahrendorf, M. (2015). Advancing biomedical imaging. Proceedings of the National Academy of Sciences, 112(47), 14424-14428.

[10] Kamat, P. V. (2012). Boosting the efficiency of quantum dot sensitized solar cells through modulation of interfacial charge transfer. Accounts of chemical research, 45(11), 1906-1915.

[11] Shor, P. W. (1998). Quantum computing. Documenta Mathematica, 1(1000), 467-486.

[12] Cao, Y., et al. (2018). Unconventional superconductivity in magic-angle graphene superlattices. Nature, 556(7699), 43-50.

[13] Schwierz, F. (2010). Graphene transistors. Nature nanotechnology, 5(7), 487-496.

[14] Vetelino, J. and A. Reghu (2017). Introduction to sensors, CRC press.

[15] Lin, X., Yang, W., Wang, K. L., & Zhao, W. (2019). Two-dimensional spintronics for low-power electronics. Nature Electronics, 2(7), 274-283.

[16] Qi, X.-L., & Zhang, S.-C. (2011). Topological insulators and superconductors. Reviews of Modern Physics, 83(4), 1057-1110.

[17] Wesche, R. (2017). High-temperature superconductors. Springer Handbook of Electronic and Photonic Materials, 1-1.

[18] Broholm, C., Cava, R. J., Kivelson, S. A., Nocera, D. G., Norman, M. R., & Senthil, T. (2020). Quantum spin liquids. Science, 367(6475), eaay0668.

[19] Misguich, G. (2010). Quantum spin liquids. Exact Methods in Low-dimensional Statistical Physics and Quantum Computing: Lecture Notes of the Les Houches Summer School: Volume 89, July 2008, 431.

[20] Broholm, C., Cava, R. J., Kivelson, S. A., Nocera, D. G., Norman, M. R., & Senthil, T. (2020). Quantum spin liquids. Science, 367(6475), eaay0668.

[21] Armitage, N. P., Mele, E. J., & Vishwanath, A. (2018). Weyl and Dirac semimetals in three-dimensional solids. Reviews of Modern Physics, 90(1), 015001.

[22] Wu, Y., Li, C., Hu, X., Ao, Y., Zhao, Y., & Gong, Q. (2017). Applications of topological photonics in integrated photonic devices. Advanced Optical Materials, 5(18), 1700357.

[23] Chorsi, H., Cheng, B., Zhao, B., Toudert, J., Asadchy, V., Shoron, O. F., & Matsunaga, R. (2022). Topological materials for functional optoelectronic devices. Advanced Functional Materials, 32(19), 2110655.

[24] Hammed, V., Bankole, A. A., Akinrotimi, O., & Ayanleye, O. (2024). Silver nanoparticles (AGNPs): A review on properties and behavior of silver at the nanoscale level.

[25] Azeez, M., Nenebi, C. T., Hammed, V., Asiam, L. K., & James, E. (2024). Developing intelligent cyber threat detection systems through quantum computing.

[26] Thangadurai, T. D., Manjubaashini, N., Nataraj, D., Gomes, V., & Lee, Y. I. (2022). A review on graphene quantum dots, an emerging luminescent carbon nanolights: Healthcare and Environmental applications. Materials Science and Engineering: B, 278, 115633.

[27] Das, S., & Saha, P. (2018). A review of some advanced sensors used for health diagnosis of civil engineering structures. Measurement, 129, 68-90