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Magnetic Materials in Quantum Computing and Future Technologies

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Abstract

Magnetic materials are increasingly recognized as critical components in the development of quantum computing and next-generation information technologies. Unlike classical electronic systems that rely solely on electric charge, quantum technologies exploit quantum mechanical phenomena such as spin, superposition, and entanglement. Magnetic materials enable control of electron spin and magnetic interactions, which are essential for spin-based qubits, quantum memories, and spintronic devices. Recent advances in nanomagnetism, two-dimensional magnetic materials, and topological magnetic systems have significantly expanded the capabilities of quantum computing platforms. Additionally, superconducting and spin-based qubit systems rely heavily on carefully engineered magnetic environments and materials with high coherence properties. This article reviews the fundamental properties of magnetic materials used in quantum technologies, discusses key material platforms such as ferromagnets, antiferromagnets, and topological magnets, and examines their role in emerging technologies including quantum computing, quantum sensing, and spintronic memory devices. Finally, the paper highlights current challenges in materials engineering and outlines future research directions for integrating magnetic materials into scalable quantum systems.

Introduction

Quantum computing represents a revolutionary shift in computational paradigms, offering the potential to solve problems that are beyond the capabilities of classical computers. Unlike classical bits that exist in either a 0 or 1 state, quantum bits (qubits) can exist simultaneously in multiple states due to the principle of superposition, enabling exponential computational power for specific tasks. Magnetic materials play a crucial role in enabling and controlling quantum information processing. In many quantum computing architectures, the spin of electrons serves as a natural quantum degree of freedom that can encode quantum information. Spin-based qubits rely on magnetic interactions and external magnetic fields to manipulate quantum states with high precision. Recent advances in material science have accelerated the development of magnetic materials tailored for quantum technologies. Superconducting materials such as aluminum and niobium are widely used in superconducting qubits, where Josephson junction circuits enable quantum operations. Additionally, novel magnetic materials including antiferromagnets, Heusler alloys, and two-dimensional magnetic heterostructures have demonstrated promising characteristics for quantum computing and spintronics applications. The integration of magnetic materials with nanoscale engineering and quantum electronics has opened new possibilities for next-generation technologies. These developments include magnetic quantum memories, spin-based logic devices, and hybrid quantum systems that combine photonics, superconductivity, and magnetism. Consequently, research into magnetic materials has become central to the future of quantum information science. Magnetic materials play a central role in quantum information science because they provide mechanisms for manipulating and controlling the quantum property known as spin. In classical electronics, information is stored through the movement of electrical charge; however, in quantum systems the intrinsic angular momentum of electrons—referred to as spin—can encode information in quantum bits or qubits. Magnetic materials provide the internal magnetic environments necessary to stabilize and manipulate these spin states. When electrons in a material interact with each other through exchange interactions, they form collective magnetic arrangements such as ferromagnetism or antiferromagnetism. These ordered states influence how spins respond to external magnetic fields, which is essential for quantum state control and quantum gate operations. The microscopic origin of magnetism lies in the alignment of electron spins and their associated magnetic moments. In ferromagnetic materials, spins tend to align in the same direction due to strong exchange interactions, resulting in a net magnetic moment across the material. In contrast, antiferromagnetic materials display alternating spin orientations that cancel out the overall magnetization while still maintaining strong internal magnetic order. Both types of materials are valuable in quantum technologies because they enable precise control over spin dynamics. Ferromagnets are often used to generate spin-polarized currents, while antiferromagnets are increasingly studied for their ultrafast spin dynamics and reduced magnetic noise, which can improve quantum coherence. At the nanoscale, magnetic behavior becomes significantly more complex and interesting due to quantum confinement effects and enhanced surface interactions. Magnetic interactions such as exchange coupling, dipole–dipole interactions, and spin–orbit coupling strongly influence how spins behave in nanostructures. Exchange coupling allows neighboring electron spins to interact directly, enabling the formation of coherent spin networks that can be used to encode and process quantum information. Dipole interactions arise from magnetic fields generated by individual spins and can lead to long-range coupling between qubits. Spin–orbit coupling, which links an electron's spin with its orbital motion around the nucleus, provides another powerful mechanism for manipulating spin states using electric fields rather than magnetic fields. Another important phenomenon in magnetic quantum systems is the existence of magnons, which are quantized spin-wave excitations within magnetic materials. Magnons represent collective oscillations of spins and can propagate through magnetic lattices carrying information without the physical movement of electrons. Because of their low energy dissipation and ability to interact with photons and superconducting circuits, magnons are considered promising candidates for quantum communication and hybrid quantum systems. Researchers are exploring magnon–photon coupling and magnon–qubit interactions to develop new platforms for quantum information transfer and storage. Spin-based qubits have emerged as one of the most promising architectures for realizing scalable quantum computers. In these systems, the quantum information is encoded in the spin state of an individual electron or nucleus confined within a nanoscale structure such as a quantum dot, impurity atom, or semiconductor defect center. The two spin orientations—commonly referred to as spin-up and spin-down—represent the fundamental quantum states of a qubit. By applying carefully controlled magnetic or electric fields, these spin states can be manipulated to perform quantum logic

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operations, enabling complex computational processes that surpass classical algorithms for certain tasks. Magnetic materials and engineered magnetic environments are essential for initializing, controlling, and reading out spin qubits. External magnetic fields are typically used to split spin energy levels through the Zeeman effect, creating distinguishable quantum states. Microwave pulses or oscillating magnetic fields can then be applied to drive transitions between these states, allowing the implementation of quantum gate operations. In some advanced systems, electric fields are also used to manipulate spins through spin–orbit coupling, enabling faster and more energy-efficient qubit control. One of the most significant advantages of spin-based qubits is their relatively long coherence time compared with other quantum computing platforms. Coherence time refers to the duration for which a quantum system can maintain its superposition state without being disrupted by environmental noise. Semiconductor spin qubits, particularly those based on silicon or diamond defect centers, have demonstrated exceptionally long coherence times due to the relatively low interaction between electron spins and surrounding atomic nuclei. This stability makes spin qubits attractive candidates for building reliable quantum processors capable of executing complex quantum algorithms. Spin qubits also offer strong compatibility with established semiconductor manufacturing technologies. Because many spin qubit platforms rely on materials such as silicon, gallium arsenide, or germanium, they can potentially be fabricated using modified versions of conventional microelectronics fabrication processes. This compatibility provides a pathway toward integrating quantum devices with existing classical electronic circuits, enabling hybrid quantum–classical computing systems. Such integration is considered a crucial step toward scaling quantum computers from experimental laboratory devices to commercially viable technologies. Furthermore, the scalability of spin-based quantum systems can be enhanced through coupling mechanisms that allow multiple qubits to interact. Exchange coupling between neighboring electron spins enables the creation of two-qubit gates, which are essential for universal quantum computation. Researchers are also investigating long-distance coupling methods using superconducting resonators, photons, and magnon-based systems. These approaches aim to connect distant qubits while maintaining coherence, thereby allowing the construction of large quantum networks capable of performing complex computations. The ongoing development of advanced magnetic materials, nanoscale fabrication techniques, and hybrid quantum architectures continues to expand the possibilities for spin-based quantum computing. As research progresses, magnetic materials will remain fundamental to the design of next-generation quantum technologies, enabling improved qubit stability, faster quantum operations, and more efficient quantum information transfer. Spintronics, or spin electronics, represents a significant advancement in information technology because it exploits both the charge and the intrinsic spin of electrons to process and store data. Traditional electronic devices rely solely on the movement of electrical charge, which often results in high energy consumption and heat generation. Spintronic systems, however, utilize the magnetic orientation of electron spins to encode information, allowing devices to operate with improved efficiency and stability. Magnetic materials are fundamental to these technologies because they provide the spin-polarized environments necessary for controlling electron spin states. By manipulating spin currents rather than charge currents, spintronics enables the development of faster and more energy-efficient electronic components. One of the most widely studied spintronic devices is the magnetic tunnel junction (MTJ), which consists of two ferromagnetic layers separated by an ultra-thin insulating barrier. When electrons tunnel through this barrier, the electrical resistance of the device changes depending on whether the magnetic layers are aligned parallel or antiparallel. This phenomenon, known as tunnel magnetoresistance, forms the basis for magnetic random access memory (MRAM). MRAM is a non-volatile memory technology, meaning it can retain stored information even when power is removed. Compared with conventional memory technologies such as DRAM and flash memory, MRAM offers advantages including faster data access, higher endurance, and lower energy consumption. These properties make MRAM a promising candidate for next-generation computing systems and data storage technologies. Spin valves represent another important class of spintronic devices. These structures consist of alternating magnetic and non-magnetic layers that control the flow of spin-polarized electrons. The resistance of the device changes depending on the relative orientation of the magnetic layers, allowing it to function as a highly sensitive magnetic sensor or memory element. Spin valves have already been widely used in hard disk drive read heads and magnetic sensing technologies. In the context of quantum technologies, spin valves and related structures can serve as building blocks for quantum memory systems capable of storing quantum information encoded in spin states. In quantum computing architectures, spintronic devices can function as quantum memory elements by preserving the spin state of electrons or nuclei for extended periods. Quantum memory is essential for storing intermediate results during quantum computations and for enabling communication between different parts of a quantum processor. Magnetic materials with strong spin coherence properties are particularly valuable in this context because they allow quantum information to remain stable despite interactions with the surrounding environment. Spintronic quantum memories may also be integrated with superconducting circuits, photonic systems, and microwave resonators to create hybrid quantum devices that combine multiple quantum technologies within a single platform. Another advantage of spintronic systems is their ability to operate with extremely low power consumption. Because spin-based operations do not require large charge currents, spintronic devices can perform switching operations with significantly reduced energy dissipation. This property is especially important for large-scale computing systems where energy efficiency and thermal management are critical challenges. Faster switching speeds also allow spintronic devices to perform data processing operations at very high frequencies, potentially surpassing the limitations of conventional semiconductor technologies. These advantages have positioned spintronics as a promising pathway toward future quantum and neuromorphic computing systems. Recent research has also focused on the development of advanced magnetic materials specifically designed for quantum technologies. Among these materials, topological magnetic materials have attracted considerable attention due to their ability to host protected quantum states. These states are often resistant to environmental disturbances such as thermal fluctuations and electromagnetic noise. The robustness of topological states makes them particularly suitable for quantum computing applications where maintaining coherence is one of the greatest technical challenges. In topological magnetic systems, electrons can move along special surface or edge states while remaining protected from scattering and decoherence, enabling stable quantum information transport. Two-dimensional magnetic materials represent another rapidly developing area of research. These materials consist of atomically thin layers in which magnetic order can persist even at extremely small thicknesses. Examples include van der Waals magnetic crystals and layered transition-metal compounds. Because these materials can be stacked with other two-dimensional materials such as graphene or transition metal dichalcogenides, researchers can engineer heterostructures with precisely controlled electronic and magnetic properties. This atomic-scale control enables the creation of customized quantum devices in which magnetism, electrical conduction, and optical interactions can be carefully tuned. Antiferromagnetic materials are also gaining attention as promising candidates for quantum technologies. Unlike ferromagnets, antiferromagnets contain opposing spin orientations that cancel out the overall magnetic moment. This property significantly reduces stray magnetic fields, which can interfere with nearby quantum components. Additionally, antiferromagnets exhibit extremely fast spin dynamics that can operate at terahertz frequencies, making them attractive for high-speed information processing systems. The combination of fast dynamics, minimal magnetic interference, and strong stability makes antiferromagnetic materials valuable for advanced quantum devices and spintronic circuits. The integration of these advanced magnetic materials with other quantum platforms is enabling the development of hybrid quantum technologies. In hybrid systems, magnetic materials can interact with superconducting circuits, optical photons, or microwave resonators to create complex quantum architectures capable of performing specialized tasks. For example, magnetic materials can be coupled with superconducting qubits to form quantum interfaces that convert information between different physical forms. Similarly, magnetic excitations such as magnons can interact with photons in optical cavities, enabling quantum communication between distant quantum processors. Looking toward future technological developments, magnetic materials are expected to play an essential role in building large-scale quantum communication networks. Quantum communication relies on the secure transfer of quantum states between distant locations, and magnetic materials may serve as key components in quantum repeaters and quantum memories that preserve quantum information during transmission. The ability of magnetic materials to store and manipulate spin states makes them particularly suitable for these applications, especially when combined with photonic and superconducting technologies. Magnetic materials are also enabling the development of ultra-sensitive sensors capable of detecting extremely weak magnetic fields. Quantum sensors based on magnetic materials can achieve unprecedented sensitivity, allowing them to detect signals from biological molecules, geological structures, or even neural activity in the human brain. These sensing technologies have potential applications in medical diagnostics, environmental monitoring, and scientific research, further demonstrating the broad impact of magnetic materials in advanced technologies.

Another important direction in this field involves the development of energy-efficient computing systems that rely on spin-based logic rather than traditional charge-based electronics. Spin-based logic circuits could dramatically reduce energy consumption in data centers and high-performance computing systems. Researchers are investigating spin-wave computing, magnonic circuits, and spin-orbit torque devices as potential alternatives to conventional transistor-based architectures. These technologies could eventually lead to computing systems that are faster, more energy-efficient, and capable of performing new types of complex computations. Advances in nanoscale fabrication and materials engineering are also expected to make quantum devices more practical and scalable. Improved control over atomic structures, magnetic interfaces, and material defects will enable the creation of highly reliable quantum components with minimal noise and improved coherence times. Researchers are exploring techniques such as molecular beam epitaxy, atomic layer deposition, and nanolithography to precisely engineer magnetic nanostructures for quantum applications. A major long-term goal in the field of quantum technologies is the development of devices that can operate at or near room temperature. Many current quantum systems require extremely low temperatures maintained by cryogenic refrigeration, which limits their practical use outside laboratory environments. By discovering new magnetic materials with strong quantum coherence and stable spin states at higher temperatures, scientists hope to reduce the need for complex cooling systems. Achieving room-temperature quantum operation would represent a significant milestone, enabling widespread adoption of quantum technologies in commercial computing, communication networks, and advanced sensing applications.

Summary

Magnetic materials form a foundational component of modern quantum technologies. Their ability to manipulate electron spin and magnetic interactions enables the development of spin-based qubits, quantum memories, and spintronic devices. Recent advances in superconducting materials, two-dimensional magnets, and topological quantum materials have expanded the possibilities for building scalable quantum computing systems. Despite significant progress, several challenges remain, including maintaining quantum coherence, reducing noise, and achieving reliable large-scale fabrication of quantum devices. Continued interdisciplinary research in physics, materials science, and nanotechnology will be essential for overcoming these challenges. As new magnetic materials and device architectures emerge, they are expected to drive breakthroughs not only in quantum computing but also in sensing, communication, and energy-efficient electronics, ultimately shaping the future of advanced technological systems.

References

[1] De Leon, N. P., et al. (2021). Materials challenges in quantum computing. Science.
[2] IBM Research. (2023). Quantum computing fundamentals.
[3] Murray, C. E. (2021). Materials in superconducting qubits. Materials Science Reports.
[4] Banerjee, N., et al. (2025). Materials roadmap for quantum technologies.
[5] Zhang, B., et al. (2024). Two-dimensional magnetic materials for quantum information processing.
[6] Tasiu, I. A. (2025). Advances in spintronics technology.
[7] National Academies. (2023). Physical qubits and quantum computing architectures.
[8] Wolf, S. A., et al. (2006). Spintronics: A spin-based electronics vision.
[9] Quantum Materials and Sensing Institute. Spin-based qubits research.
[10] Spin Quanta. Types of qubits in quantum computing.
[11] Samaterials. Superconducting materials used in quantum devices.
[12] Patsnap Research. Magnetic materials in spintronic devices.