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Advance Physics Letter

ISSN: 2349-1094

Volume 11 Issue 02, 2022

A Review of Magnetic Materials and Spintronics

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Peer Review Information

Submission: 05 July 2022

Revision: 23 July 2022

Acceptance: 11 Aug 2022

Keywords

Magnetic materials, spintronics, ferromagnetism, magnetoresistance, spin polarization, magnetic storage, spin transport

Abstract

Magnetic materials play a central role in modern technology, from traditional applications such as electric motors and data storage to emerging fields like spintronics. Spintronics, or spin-based electronics, exploits not only the charge of electrons but also their intrinsic spin and associated magnetic moment to store, process, and transmit information. This review presents a comprehensive overview of magnetic materials and their evolution toward spintronic applications. Fundamental magnetic interactions, classification of magnetic materials, and spin-dependent transport phenomena are discussed. Key spintronic concepts such as giant magnetoresistance, tunneling magnetoresistance, spin injection, and spin transfer torque are reviewed. A comparative analysis of magnetic materials used in spintronics is provided, followed by a discussion of technological challenges, recent advances, and future directions in magnetic and spin-based devices.

Introduction

Magnetic materials have been studied for centuries, yet their importance continues to grow with the rapid advancement of information and communication technologies. Traditional electronics relies solely on the charge of electrons to perform computation and data storage. However, as device dimensions approach fundamental physical limits, conventional charge-based electronics faces challenges related to power dissipation, scaling, and speed. Spintronics emerges as a promising paradigm that leverages the intrinsic spin of electrons, offering new functionalities and improved performance (Žutić et al., 2004).

Magnetism in materials originates from the spin and orbital angular momentum of electrons. At the atomic level, exchange interactions between neighboring spins determine whether a material exhibits ferromagnetic, antiferromagnetic, or other magnetic ordering. These collective spin arrangements give rise to macroscopic magnetic properties that can be harnessed for technological applications (Cullity & Graham, 2011).

Magnetic materials are broadly classified into diamagnetic, paramagnetic, ferromagnetic, antiferromagnetic, and ferrimagnetic materials. Among these, ferromagnetic and ferrimagnetic materials are the most technologically significant due to their spontaneous magnetization and hysteresis behavior. Classic ferromagnets such as iron, cobalt, and nickel have been widely used in permanent magnets, transformers, and magnetic recording media (Kittel, 2005).

The development of magnetic storage technologies marked a major milestone in the information age. Magnetic tapes, hard disk drives, and magnetic random-access memory (MRAM) rely on the ability to manipulate and detect magnetic states at increasingly smaller scales. However, conventional magnetic devices typically require large currents and magnetic fields, leading to energy inefficiencies and scaling limitations.

Spintronics addresses these challenges by utilizing spin-dependent transport phenomena. The discovery of giant magnetoresistance (GMR) in magnetic multilayers in 1988 revolutionized data storage by enabling highly sensitive magnetic read heads. This breakthrough, awarded the Nobel Prize in Physics in 2007, demonstrated that electron transport can be strongly influenced by spin alignment in layered magnetic structures (Baibich et al., 1988).

Subsequent discoveries such as tunneling magnetoresistance (TMR) in magnetic tunnel junctions further advanced spintronic technology. TMR-based devices form the core of modern MRAM, offering non-volatility, fast switching speeds, and high endurance. Spin transfer torque (STT) and spin–orbit torque (SOT) mechanisms enable electrical control of magnetization without external magnetic fields, significantly reducing power consumption (Ralph & Stiles, 2008).

Materials science plays a crucial role in spintronics. Ferromagnetic metals, magnetic semiconductors, half-metallic ferromagnets, and antiferromagnets are actively investigated for their spin polarization, anisotropy, and spin coherence properties. Recently, two-dimensional magnetic materials and topological materials have expanded the scope of spintronics, enabling ultra-thin, flexible, and low-power devices.

This review provides a comprehensive examination of magnetic materials and spintronics, covering fundamental magnetic interactions, key materials systems, spin-dependent transport phenomena, and practical applications. The objective is to highlight how advances in magnetic materials underpin the rapid evolution of spintronic technologies.

Literature Review

Kittel (2005) explained fundamental magnetic interactions.

Cullity and Graham (2011) reviewed magnetic material properties.

Žutić et al. (2004) defined the scope of spintronics.

Baibich et al. (1988) discovered giant magnetoresistance.

Binasch et al. (1989) confirmed GMR in multilayers.

Fert (2008) reviewed GMR and spintronics.

Parkin et al. (2004) demonstrated high TMR devices.

Ralph and Stiles (2008) analyzed spin transfer torque.

Wolf et al. (2001) discussed spin-based electronics.

Jungwirth et al. (2016) reviewed antiferromagnetic spintronics.

Chappert et al. (2007) reviewed magnetic memories.

Železný et al. (2018) studied spin–orbit torques.

Kent and Worledge (2015) reviewed MRAM technology.

Dietl et al. (2000) studied magnetic semiconductors.

Hirohata et al. (2020) reviewed spintronic materials roadmap.

Manchon et al. (2015) reviewed spin–orbit effects.

Fert et al. (2013) reviewed skyrmions.

Tokura et al. (2020) studied chiral magnetism.

Parkin (2008) reviewed magnetic storage evolution.

Zutic and Fabian (2007) reviewed spin injection.

Awschalom et al. (2013) reviewed spintronics fundamentals.

Gong et al. (2017) studied 2D magnetic materials.

Bader and Parkin (2010) reviewed spintronics overview.

Baltz et al. (2018) reviewed antiferromagnetic spintronics.

Yang et al. (2015) studied domain wall motion.

Comparative Table and Analysis

Table 1: Magnetic Materials for Spintronic Applications

Material Type	Magnetic Order	Key Properties	Advantages	Limitations	Applications
Ferromagnetic metals	FM	High spin polarization	Mature technology	Eddy losses	HDDs, MRAM
Magnetic semiconductors	FM	Electrical tunability	Spin injection	Low Tc	Spin transistors
Half-metallic ferromagnets	FM	100% polarization	High efficiency	Fabrication issues	Spin valves
Antiferromagnets	AFM	Zero net magnetization	Fast dynamics	Detection difficulty	THz spintronics
2D magnetic materials	FM/AFM	Atomic thickness	Flexibility	Stability	Nano-spintronics

Analysis:
The comparative analysis of magnetic materials used in spintronics reveals how subtle differences in magnetic ordering, electronic structure, and spin–orbit coupling determine device functionality, efficiency, and scalability. Unlike conventional electronics, where performance is primarily dictated by charge mobility, spintronic systems rely on spin polarization, coherence, and interfacial effects, making materials selection a critical design parameter.

1. Ferromagnetic Metals vs. Magnetic Semiconductors
Ferromagnetic metals such as iron, cobalt, and nickel have historically dominated magnetic device technologies due to their strong spontaneous magnetization and high Curie temperatures. Their electronic structure allows efficient spin polarization, making them ideal for spin valves and magnetic tunnel junctions. However, metallic ferromagnets suffer from significant Joule heating and limited tunability of spin properties using electric fields.
Magnetic semiconductors, in contrast, combine semiconducting behavior with magnetic ordering. This dual nature allows for electrical control of magnetism through carrier concentration, offering a direct pathway toward integrating spintronic functionality with conventional semiconductor electronics. Nevertheless, most magnetic semiconductors exhibit low Curie temperatures, limiting their practical applicability at room temperature. The comparison underscores a fundamental trade-off between robustness and tunability.

2. Half-Metallic Ferromagnets and Spin Polarization Efficiency
Half-metallic ferromagnets occupy a unique position in spintronics due to their theoretically 100% spin polarization at the Fermi level. This property arises from a band structure in which one spin channel is metallic while the other is insulating. As a result, half-metals are ideal candidates for achieving high magnetoresistance ratios in spin valves and tunnel junctions.
In practice, however, interface imperfections, atomic disorder, and thermal fluctuations often reduce effective spin polarization. Compared to conventional ferromagnets, half-metals offer superior theoretical performance but require advanced fabrication techniques to preserve their electronic structure at interfaces. This comparison highlights the critical role of materials engineering in realizing predicted spintronic advantages.

3. Antiferromagnets vs. Ferromagnets in Spintronics
Antiferromagnetic materials have recently emerged as promising alternatives to ferromagnets in spintronic applications. Unlike ferromagnets, antiferromagnets exhibit no net magnetization due to antiparallel spin alignment, making them immune to stray magnetic fields and cross-talk. This property is particularly advantageous for high-density device integration.
Additionally, antiferromagnets exhibit ultrafast spin dynamics in the terahertz regime, far exceeding the operational speeds of ferromagnetic devices. However, the absence of net magnetization complicates readout and manipulation. Comparatively, while ferromagnets offer straightforward detection, antiferromagnets provide superior speed and stability, signaling a paradigm shift in spintronics.

4. Two-Dimensional Magnetic Materials and Dimensional Scaling
Two-dimensional magnetic materials represent a major advance in spintronics by enabling magnetism at the atomic scale. Materials such as CrI_3 and Fe_3GeTe_2 retain magnetic ordering down to monolayer thickness, defying earlier theoretical expectations. Reduced dimensionality enhances quantum confinement and interfacial effects, allowing strong control over spin states using electric fields and proximity coupling.
Compared to bulk magnetic materials, 2D magnets offer exceptional scalability and compatibility with van der Waals heterostructures. However, environmental stability and low ordering temperatures remain significant challenges. This comparison emphasizes dimensionality as a key tuning parameter for future spintronic architectures.

5. Spin Transport Mechanisms: GMR vs. TMR
Giant magnetoresistance (GMR) and tunneling magnetoresistance (TMR) are foundational effects in spintronics, yet they operate through fundamentally different transport mechanisms. GMR relies on spin-dependent scattering in metallic multilayers, while TMR involves quantum tunneling through an insulating barrier. TMR typically achieves much higher resistance changes than GMR, making it preferable for memory applications such as MRAM. However, TMR performance is highly sensitive to barrier thickness and interface quality. The comparison illustrates how quantum mechanical tunneling offers superior performance at the cost of increased fabrication complexity.

6. Spin Transfer Torque vs. Spin–Orbit Torque
Spin transfer torque (STT) and spin–orbit torque (SOT) represent two mechanisms for electrically controlling magnetization. STT relies on spin-polarized currents passing directly through magnetic layers, whereas SOT exploits strong spin–orbit coupling in adjacent non-magnetic layers to generate spin currents.
Comparatively, SOT offers faster switching and improved device endurance, as it separates read and write paths. However, SOT devices often require additional layers and precise materials engineering. This analysis demonstrates how torque mechanisms influence energy efficiency and device architecture.

7. Skyrmions and Topological Spin Textures
Magnetic skyrmions are nanoscale, topologically protected spin textures that can be manipulated with extremely low current densities. Compared to conventional domain walls, skyrmions offer enhanced stability and reduced energy consumption, making them promising candidates for next-generation memory and logic devices.
Nevertheless, challenges remain in stabilizing skyrmions at room temperature and achieving reliable creation and deletion. Their comparison with traditional magnetic textures highlights the growing importance of topology in spintronic material design.

8. Integrated Analytical Perspective
This expanded analysis demonstrates that progress in spintronics is not driven by a single material or mechanism but by the interplay of magnetic order, dimensionality, topology, and spin–orbit coupling. Ferromagnets, antiferromagnets, and emerging low-dimensional systems each offer distinct advantages and limitations.
Future spintronic technologies will likely employ hybrid architectures that combine multiple material classes to optimize performance. The comparative understanding of magnetic materials thus serves as a roadmap for designing scalable, energy-efficient, and high-speed spin-based devices.

Discussion
The rapid progress in magnetic materials and spintronics reflects a broader transition from classical magnetism to quantum-engineered spin systems. Traditional ferromagnets remain indispensable due to their robustness and ease of integration. However, their reliance on external magnetic fields and relatively slow dynamics limit further performance improvements.
Spintronic mechanisms such as GMR and TMR have already transformed data storage technology by enabling higher density and faster readout. The emergence of STT- and SOT-based devices has further reduced power consumption and improved scalability. Nevertheless, challenges related to material defects, interface quality, and thermal stability persist.
Antiferromagnetic spintronics represents a promising frontier due to ultrafast spin dynamics and immunity to external magnetic fields. Similarly, topological spin textures such as skyrmions offer energy-efficient information carriers. Continued advances in materials synthesis and characterization will be critical for translating these concepts into practical devices.

Conclusion
Magnetic materials and spintronics have reshaped modern information technology by introducing spin as an active degree of freedom. This review has examined fundamental magnetic interactions, key material systems, and spin-dependent transport phenomena that underpin spintronic devices.
While ferromagnetic metals remain central to current technologies, emerging materials such as antiferromagnets, half-metals, and two-dimensional magnets promise transformative advances. Future research will focus on improving material quality, device scalability, and energy efficiency.
In conclusion, magnetic materials and spintronics will play a vital role in next-generation computing, memory, and sensing technologies, bridging the gap between classical electronics and quantum information science.

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