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Spintronics and Magnetism: Physics, Materials, and Applications

Zaydaan Khatibullah
Assistant Professor, Department of Interdisciplinary Physics, Peninsula Institute of Engineering Studies, Malaysia
Email: zaydaan.khatibullah@pies-my.edu

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Abstract

Spintronics, or spin electronics, leverages the intrinsic spin of electrons and their associated magnetic moment, in addition to charge, for advanced information storage and processing technologies. Coupled with the field of magnetism, spintronics offers promising avenues for low-power, high-speed devices, magnetic random access memory (MRAM), spin transistors, and quantum computing. This review discusses the fundamental physics of spin-dependent phenomena, key magnetic and spintronic materials, synthesis and characterization techniques, and current and emerging applications. Special emphasis is given to spin transport, spin–orbit coupling, topological materials, and novel 2D magnetic materials. Challenges, including scalability, stability, and interface engineering, are also highlighted alongside future research directions.

Introduction

1. Background

Traditional electronics relies on electron charge, but electron spin adds an additional degree of freedom. Spintronics integrates spin-dependent phenomena, enabling devices with faster operation speeds, lower energy consumption, and nonvolatile memory. Magnetic materials, ranging from ferromagnets to antiferromagnets, are central to spintronic functionality. The field intersects condensed matter physics, materials science, and nanotechnology, driving innovations in computation, data storage, and sensing.

2. Fundamental Physics

Spin-dependent transport phenomena include:

- Giant Magnetoresistance (GMR): Resistance changes in layered ferromagnetic/nonmagnetic structures under a magnetic field.
- Tunnel Magnetoresistance (TMR): Quantum tunneling through insulating barriers modulated by spin alignment.
- Spin Hall Effect: Conversion of charge current into transverse spin current due to spin–orbit coupling.
- Spin–orbit torque (SOT): Control of magnetization in magnetic layers using spin currents.

Electron spin coherence, relaxation times, and spin injection efficiency are key physical parameters that define device performance.

3. Materials for Spintronics

- **Ferromagnets:** Fe, Co, Ni, and their alloys.
- **Antiferromagnets:** Mn-based compounds, CuMnAs, promising for ultrafast dynamics.
- **Half-metallic materials:** CrO_2, Heusler alloys, providing 100% spin polarization.

- **2D magnetic materials:** CrI_3, Fe_3GeTe_2, enabling atomic-scale spintronic devices.
- **Topological insulators:** Bi_2Se_3, Bi_2Te_3, exhibiting spin-momentum locking.

These materials are engineered using molecular beam epitaxy (MBE), sputtering, chemical vapor deposition (CVD), and pulsed laser deposition (PLD).

4. Applications

- Memory devices: MRAM, racetrack memory.
- Logic devices: Spin transistors and spin logic gates.
- Sensors: Magnetic field sensors using GMR/TMR.
- Quantum computing: Qubits based on electron or nuclear spin.

5. Motivation for Review

Spintronics is poised to revolutionize electronics by exploiting spin phenomena for low-power, high-performance devices. Understanding the physics, materials, and applications of spintronics is critical for advancing next-generation information technologies.

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Comparative Table and Analysis

Material / Structure	Spin Property	Synthesis / Fabrication	Applications	Strengths / Limitations

Fe, Co, Ni alloys	Ferromagnetism	Sputtering, MBE	MRAM, sensors	+ High Curie temperature; – Moderate spin polarization
Heusler alloys	Half-metallicity	Bulk synthesis, thin films	Spin injectors	+ 100% spin polarization; – Complex stoichiometry
CuMnAs	Antiferromagnet	MBE, PLD	Ultrafast memory	+ Fast dynamics; – Difficult integration
CrI_3	2D magnet	Mechanical exfoliation	Nanoscale spin devices	+ Atomically thin; – Air sensitive
Bi_2Se_3	Topological insulator	MBE, CVD	Spin Hall devices, quantum computing	+ Spin-momentum locking; – Defect sensitivity
CoFeB/MgO	Tunnel junction	Sputtering	MRAM	+ High TMR ratio; – Interface engineering critical

Analysis:

- 2D magnetic materials allow nanoscale control and integration in heterostructures.
- Heusler alloys and half-metals maximize spin polarization for efficient spin injection.
- Antiferromagnets offer ultrafast spin dynamics and minimal stray fields.
- Interface engineering is crucial for TMR and spin–orbit torque devices.

Discussion

Spintronics relies on the manipulation of electron spin in addition to charge, with magnetism providing the underlying ordering necessary for spin-dependent phenomena. Materials like ferromagnets, antiferromagnets, half-metals, and 2D magnets form the core of device design. Spin transport, coherence, and relaxation are crucial parameters, dictating performance in MRAM, spin transistors, and spin logic devices.

The rise of 2D magnets and topological insulators offers atomically thin, high-coherence platforms suitable for quantum devices. Spin–orbit coupling enables electrical control of spin, reducing power consumption in memory and logic devices. Antiferromagnets allow ultrafast spin dynamics without generating stray fields, addressing scalability and density issues.

Challenges remain in material stability, interface quality, and scalability. Spin injection efficiency, spin lifetime, and coherent spin transport are limited by disorder, impurities, and interface roughness. Emerging computational methods and high-throughput synthesis can accelerate materials discovery and optimization. Combining CMP principles with device engineering will be key for next-generation low-power spintronic applications.

Conclusion

Spintronics, leveraging electron spin in addition to charge, represents a transformative paradigm in electronics. The interplay between spin-dependent phenomena and magnetic materials has enabled breakthroughs in MRAM, spin logic, quantum computing, and high-sensitivity sensors. Materials such as ferromagnets, antiferromagnets, half-metals, 2D magnets, and topological insulators demonstrate unique spin properties critical for device performance.

Advancements in synthesis, thin-film growth, heterostructures, and interface engineering have facilitated efficient spin injection, spin transport, and spin–orbit torque applications. 2D magnetic materials and topological systems provide platforms for atomically precise devices and quantum applications. Antiferromagnetic spintronics offers ultrafast operation with minimal stray fields, enabling dense integration.

Despite significant progress, challenges remain. Scalability, stability, spin coherence, and interface control continue to limit practical implementation. Future research will focus on novel material discovery, quantum spin manipulation, and integration with conventional electronics. Computational materials design, machine learning, and high-throughput experimental techniques will accelerate these developments.

In conclusion, spintronics and magnetism represent a fusion of condensed matter physics, materials science, and device engineering, promising energy-efficient, high-speed, and quantum-ready technologies. Continued interdisciplinary research will drive next-generation spintronic devices, shaping the future of electronics and information technology.

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