

**SPINTRONICS AS A PARADIGM OF POST-SILICON NANO-ELECTRONICS:  
SCIENTIFIC NOVELTY, TOPOLOGICAL APPROACHES AND ULTRAFAST SPIN  
DYNAMICS**

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**Abstract**

Spintronics has evolved from a phenomenon-driven research domain into a strategic technological platform for post-silicon nanoelectronics. This paper presents a systematic analysis of the scientific novelty underlying contemporary spintronic research. Particular attention is devoted to antiferromagnetic spintronics, spin-orbit torque memory architectures, magnetic skyrmions, topological quantum materials, and neuromorphic spin devices. It is demonstrated that the modern stage of spintronics is characterized by a transition toward terahertz spin dynamics, topological stabilization of information states, symmetry-engineered control mechanisms, and functional integration with CMOS technology. The study identifies material, dynamical, topological, and architectural dimensions of novelty that collectively redefine the physical principles of information processing.

**Keywords:** spintronics, antiferromagnetic order, spin-orbit torque, skyrmions, topological insulators, terahertz dynamics, neuromorphic systems.

**Introduction**

The discovery of giant magnetoresistance by Albert Fert and Peter Grünberg in 1988 [1] marked the conceptual birth of spintronics. For the first time, electronic transport was explicitly linked to spin-dependent scattering, establishing that magnetization configuration can directly modulate electrical resistance. This finding not only led to the development of magnetic read heads and MRAM technologies but also introduced spin as an operational variable in solid-state electronics.

Over the past three decades, the field has undergone a structural transformation. While early spintronic systems relied on ferromagnetic multilayers and magnetization reversal, contemporary research is driven by symmetry principles, relativistic spin-orbit effects, and topological invariants. The limitations of Moore's law scaling, increasing power density, and the von Neumann bottleneck have further stimulated the search for fundamentally different information carriers. Spin-based architectures offer non-volatility, reduced Joule heating, and compatibility with nanoscale integration.

The objective of this work is not merely to review recent advances but to articulate the scientific novelty that distinguishes the current stage of spintronics from its classical phase.

**Antiferromagnetic Spintronics: Ultrafast Order Without Magnetization**

Antiferromagnets, characterized by compensated magnetic sublattices, were historically considered unsuitable for device applications due to the absence of net magnetization. This paradigm was overturned by theoretical and experimental studies demonstrating electrical control of antiferromagnetic order.

Seminal contributions by Tomas Jungwirth and collaborators [2] established that spin-orbit torque can reorient the Néel vector in materials such as CuMnAs and Mn<sub>2</sub>Au. Unlike ferromagnets, antiferromagnets exhibit intrinsic resonance frequencies in the terahertz regime, enabling ultrafast switching beyond gigahertz limitations.

The novelty of this direction can be formulated in three dimensions:

- Dynamical novelty: switching governed by exchange-enhanced spin dynamics reaching THz frequencies;

- Symmetry-based control: manipulation of staggered magnetization via relativistic spin-orbit coupling;
  - Zero stray field operation: absence of dipolar fields allows extreme integration density.
- This shift from magnetization-based to order-parameter-based information encoding represents a conceptual redefinition of spintronic functionality.

### **Spin-Orbit Torque Architectures and Energy Scaling**

The emergence of Spin-Orbit Torque MRAM (SOT-MRAM) signifies a transition from current-induced spin transfer to symmetry-driven spin conversion mechanisms. In these systems, charge current flowing in a heavy metal layer generates a transverse spin current via the spin Hall effect, exerting torque on an adjacent magnetic layer.

Industrial efforts led by companies such as Samsung Electronics and TSMC demonstrate the scalability of SOT devices toward sub-10-nm nodes [3].

The spin current density can be expressed as:

$$J_s = \theta_{SH} \frac{\hbar}{2e} J_c$$

where  $\theta_{SH}$  is the spin Hall angle and  $J_c$  is the charge current density.

The torque acting on magnetization is proportional to:

$$\tau_{SOT} \propto \theta_{SH} J_c$$

The architectural novelty lies in separating read and write paths, reducing tunnel barrier degradation and enhancing endurance ( $>10^{12}$  cycles). From an energetic standpoint, SOT-MRAM approaches the regime of sub-picojoule switching, positioning spintronics as a competitive candidate for energy-constrained computing systems.

### **Magnetic Skyrmions: Topology as Information Stability**

Magnetic skyrmions are nanoscale spin textures characterized by a nontrivial topological charge. Their stabilization arises from the Dzyaloshinskii-Moriya interaction and interfacial symmetry breaking.

According to comprehensive analyses [4], skyrmions can be displaced by ultra-low current densities, several orders of magnitude smaller than those required for domain-wall motion. Their topological charge:

$$Q = \frac{1}{4\pi} \int \mathbf{m} \cdot \left( \frac{\partial \mathbf{m}}{\partial x} \times \frac{\partial \mathbf{m}}{\partial y} \right) dx dy$$

acts as a conserved quantity, protecting the structure against continuous deformation.

The novelty here is fundamentally topological: information is encoded not in a binary magnetization direction but in a topological invariant. This enables racetrack memory concepts with unprecedented density and robustness.

### **Topological Quantum Materials and Spin-Momentum Locking**

The theoretical prediction of the quantum spin Hall effect by Charles L. Kane and Eugene Mele [5] established the existence of materials with protected surface states governed by time-reversal symmetry.

Topological insulators exhibit spin-momentum locking, meaning that electron momentum uniquely determines spin orientation. This property enables highly efficient charge-to-spin conversion without ferromagnetic elements.

Such materials introduce:

- **Material novelty:** spin-polarized transport emerging from band topology;

- **Quantum protection:** suppression of backscattering;
- **Interface engineering opportunities:** hybrid CMOS–topological heterostructures.

This convergence of topology and spin transport signals the emergence of quantum spintronics as a new subdiscipline.

#### **Spintronics and Neuromorphic Architectures**

The stochastic switching behavior of magnetic tunnel junctions provides a physical basis for probabilistic computation. As reviewed in [6], spintronic nanodevices can function as artificial synapses and neurons with intrinsic non-volatility and nanoscale footprint.

The novelty lies in collapsing the memory–logic dichotomy: storage and processing coexist within the same physical element. This architectural integration mitigates data transfer bottlenecks and reduces system-level energy consumption.

Spin-based neuromorphic systems thus redefine computation not as deterministic transistor switching, but as physics-driven state evolution.

#### **Conclusions**

The evolution of spintronics from the discovery of giant magnetoresistance to contemporary topological and quantum-engineered systems reflects a profound transformation of information technology paradigms. The foundational work on giant magnetoresistance by Albert Fert and Peter Grünberg [1] established the principle that electronic transport can be modulated through spin-dependent scattering mechanisms. This discovery marked the beginning of spin-based electronics and laid the groundwork for magnetoresistive memory technologies.

At the present stage, the field has expanded far beyond magnetoresistive multilayers. One of the most significant breakthroughs is the emergence of antiferromagnetic spintronics. As demonstrated in [2], electrical manipulation of the Néel order parameter enables ultrafast spin dynamics potentially reaching the terahertz regime. Unlike ferromagnetic systems, antiferromagnets exhibit zero net magnetization, eliminating stray fields and allowing dense device integration. These characteristics define a clear dynamical and symmetry-driven novelty in comparison with earlier spintronic approaches.

A second major direction concerns spin–orbit torque–based device architectures. The physical principles of spin–orbit logic and magnetoelectric nodes described in [3] show that charge-to-spin conversion via the spin Hall effect enables efficient magnetization switching with reduced current density. This mechanism enhances device endurance and supports CMOS compatibility, positioning SOT-based memory as a realistic candidate for scalable non-volatile technologies. Thus, spin–orbit torque introduces both energetic and architectural novelty into spintronic design.

Topological stabilization of magnetic textures further extends the conceptual boundaries of the field. Magnetic skyrmions, analyzed comprehensively in [4], represent nanoscale spin configurations protected by a nontrivial topological charge. Their stability against perturbations and low-current-driven mobility enable ultrahigh-density and low-power information storage. In this context, topology becomes not merely a mathematical abstraction but a practical tool for robust data encoding.

The integration of topological quantum materials also plays a crucial role in contemporary spintronics. The theoretical framework of the quantum spin Hall effect proposed in [5] demonstrated the existence of spin–momentum–locked surface states in topological insulators. These states enable efficient spin-current generation without conventional ferromagnetic layers, thereby reducing dissipative losses and expanding material design strategies. This development represents a transition toward quantum-material-driven spin transport.

Finally, spintronic nanodevices have shown strong potential in neuromorphic computing systems. As discussed in [6], magnetic tunnel junctions can operate as stochastic neurons and

synapses, combining non-volatility with probabilistic switching behavior. The co-localization of memory and computation mitigates the von Neumann bottleneck and significantly reduces energy consumption in artificial neural networks. This architectural shift highlights the interdisciplinary convergence of spintronics, materials science, and artificial intelligence.

In summary, the scientific novelty of modern spintronics can be classified into four interconnected dimensions:

1. **Dynamical novelty** — ultrafast antiferromagnetic spin dynamics [2];
2. **Energetic and architectural novelty** — spin-orbit torque-based switching mechanisms [3];
3. **Topological novelty** — stability ensured by invariant skyrmion charge [4];
4. **Quantum-material novelty** — topology-driven spin transport phenomena [5].

Together, these developments indicate that spintronics is transitioning from a magnetoresistive technology platform initiated by giant magnetoresistance [1] to a comprehensive post-silicon framework integrating ultrafast dynamics, topological protection, and neuromorphic architectures [6]. Continued advances in materials engineering and scalable fabrication will determine the pace of its industrial adoption and its ultimate impact on next-generation computing systems.

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