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Article

# Spintronics and Its Practical Realization

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**Abstract:** Spintronics, or spin electronics, describes a developmental approach to information processing and storage by utilizing the intrinsic spin of electrons in addition to their charge. Unlike conventional electronics those relies solely on the movement of charge, spintronics exploits the spin degree of freedom in which it enables some unique functionalities and potentially reducing power consumption. This article elaborates the fundamental principles of spin currents, materials that enable spintronic devices, and the some challenges which are associated with the integration of spin-based logic and memory into existing technologies. In this, we also explore the current state of spintronics, some of its practical applications in areas such as magnetic memory, spin-based logic circuits, and quantum computing, and discuss future directions for advancing this promising field. By discussing the unique properties of spin currents and their potential to restructure the field of electronics, this article aims to contribute to the ongoing development of next-generation technologies.

**Keywords:** spintronics; spin currents; quantum computing

## 1. Introduction

The field of spintronics has emerged as a transformative approach to electronics, offering new possibilities for low-power memory, logic, and quantum computing. Traditional electronics, based on the charge of electrons, faces limitations in terms of power consumption and miniaturization as devices shrink to nanoscale dimensions. Spintronics, by contrast, exploits the spin of electrons, a quantum mechanical property that can be manipulated to store and process information. This paper explores the principles of spin currents, the materials that enable spintronic devices, and the challenges in integrating these devices into practical applications.

## 2. Principles of Spin Currents

### 2.1. Spin Current and Spin Polarization

The central concept in spintronics is the **spin current**, which represents the flow of spin angular momentum. The spin current density  $\mathbf{J}_s$  is defined as:

$$\mathbf{J}_s = \frac{\hbar}{2e} \mathbf{J}_c \cdot \mathbf{P},$$

where:

- $\hbar$  is the reduced Planck's constant,
- $e$  is the electron charge,
- $\mathbf{J}_c$  is the charge current density, and
- $\mathbf{P}$  is the spin polarization vector, which quantifies the alignment of electron spins.

In magnetic materials, the spin polarization  $\mathbf{P}$  can be significant which often leads to a strong coupling between charge and spin currents. This coupling is the basis for many spintronic devices, such as magnetic random-access memory (MRAM) and spin-based logic circuits.

## 2.2. Spin Hall Effect and Inverse Spin Hall Effect

The **spin Hall effect (SHE)** is a key phenomenon in spintronics, in which a charge current  $\mathbf{J}_c$  generates a transverse spin current  $\mathbf{J}_s$  due to spin-orbit coupling. The spin Hall angle  $\theta_{SH}$  characterizes the efficiency of this conversion:

$$\theta_{SH} = \frac{|\mathbf{J}_s|}{|\mathbf{J}_c|}.$$

Conversely, the **inverse spin Hall effect (ISHE)** occurs when a spin current  $\mathbf{J}_s$  generates a transverse charge current  $\mathbf{J}_c$ . This effect is described by:

$$\mathbf{J}_c = \theta_{SH} \mathbf{J}_s \times \boldsymbol{\sigma},$$

where  $\boldsymbol{\sigma}$  is the spin polarization direction. These effects are very important for the generation and detection of spin currents in spintronic devices.

## 3. Materials for Spintronics

### 3.1. Heavy Metals

Heavy metals like platinum (Pt) and tantalum (Ta) are widely used in spintronics due to their strong **spin-orbit coupling (SOC)**, which facilitates the **spin Hall effect (SHE)**. The spin Hall angle  $\theta_{SH}$  quantifies the efficiency of charge-to-spin current conversion and is defined as:

$$\theta_{SH} = \frac{|\mathbf{J}_s|}{|\mathbf{J}_c|},$$

where  $\mathbf{J}_s$  is the spin current density and  $\mathbf{J}_c$  is the charge current density. The spin current density  $\mathbf{J}_s$  generated by the SHE can be expressed as:

$$\mathbf{J}_s = \theta_{SH} (\mathbf{J}_c \times \boldsymbol{\sigma}),$$

where  $\boldsymbol{\sigma}$  is the spin polarization vector. For heavy metals like Pt and Ta, the spin Hall angle  $\theta_{SH}$  typically ranges from 0.01 to 0.1. The spin diffusion length  $\lambda_{sd}$  in these materials is given by:

$$\lambda_{sd} = \sqrt{D\tau_{sf}},$$

where  $D$  is the diffusion coefficient and  $\tau_{sf}$  is the spin-flip relaxation time.

### 3.2. Ferromagnetic Insulators

Ferromagnetic insulators like **yttrium iron garnet (YIG)** are mostly used in devices that depends on the **spin Seebeck effect (SSE)**, in which a temperature gradient  $\nabla T$  generates a spin current  $\mathbf{J}_s$  without an accompanying charge current. The SSE is described by:

$$\mathbf{J}_s = -\sigma_s \nabla T,$$

where  $\sigma_s$  is the spin-dependent Seebeck coefficient. In YIG, the spin current is mediated by magnons, and the spin current density can be expressed as:

$$\mathbf{J}_s = \frac{\hbar}{2e} \mathbf{J}_m \cdot \mathbf{P},$$

where  $\mathbf{J}_m$  is the magnon current density and  $\mathbf{P}$  is the spin polarization vector. YIG exhibits low magnetic damping ( $\alpha \approx 10^{-4}$ ), given by:

$$\alpha = \frac{\gamma \Delta H}{2\omega},$$

where  $\gamma$  is the gyromagnetic ratio,  $\Delta H$  is the linewidth of the ferromagnetic resonance, and  $\omega$  is the angular frequency.

### 3.3. Topological Insulators

Topological insulators (TIs), like **bismuth selenide (Bi<sub>2</sub>Se<sub>3</sub>)**, shows **strong spin-momentum locking** in their surface states. The surface states of TIs are described by a Dirac-like Hamiltonian:

$$H = v_F (\boldsymbol{\sigma} \times \mathbf{k}) \cdot \hat{\mathbf{z}},$$

where  $v_F$  is the Fermi velocity,  $\boldsymbol{\sigma}$  is the vector of Pauli matrices,  $\mathbf{k}$  is the electron momentum, and  $\hat{\mathbf{z}}$  is the unit vector normal to the surface. The spin current density  $\mathbf{J}_s$  in TIs can be expressed as:

$$\mathbf{J}_s = \frac{\hbar}{2e} \mathbf{J}_c \cdot \mathbf{P},$$

where  $\mathbf{P}$  is the spin polarization vector. The quantized conductance of the edge states in a 2D topological insulator is given by:

$$G = \frac{e^2}{h}.$$

## 4. Applications of Spintronics

### 4.1. Magnetic Random-Access Memory (MRAM)

MRAM is a non-volatile memory technology that uses the orientation of electron spins to store information. The **spin-transfer torque (STT)** effect, where a spin current exerts a torque on a magnetic layer, is used to switch the magnetization of memory cells. The switching efficiency is given by:

$$\tau_{STT} = \frac{\hbar}{2e} \frac{\mathbf{J}_s \cdot \mathbf{M}}{M_s},$$

where:

- $\mathbf{J}_s$  is the spin current density,
- $\mathbf{M}$  is the magnetization vector,
- $M_s$  is the saturation magnetization,
- $\hbar$  is the reduced Planck's constant,
- $e$  is the electron charge.

The STT effect arises from the transfer of angular momentum from the spin-polarized current to the magnetic layer. The torque  $\tau_{STT}$  can be expressed in terms of the spin polarization vector  $\mathbf{P}$  and the magnetization vector  $\mathbf{M}$ :

$$\tau_{STT} = \frac{\hbar}{2e} \frac{\mathbf{J}_s \cdot (\mathbf{P} \times \mathbf{M})}{M_s}.$$

The critical current density  $J_c$  required to switch the magnetization is given by:

$$J_c = \frac{2e}{\hbar} \frac{\alpha M_s t}{\eta},$$

where:

- $\alpha$  is the Gilbert damping parameter,
- $t$  is the thickness of the magnetic layer,
- $\eta$  is the spin polarization efficiency.

MRAM offers a number of advantages over conventional memory technologies, including faster read/write speeds, lower power consumption, and higher endurance. The energy required to switch a bit in MRAM is significantly lower than in traditional DRAM or flash memory, making it a promising candidate for next-generation memory technologies.

#### 4.2. Spin-Based Logic Circuits

Spin-based logic devices exploit the spin degree of freedom to perform logic operations with potentially lower power consumption than conventional CMOS technology. For example, **all-spin logic (ASL)** devices use spin currents to propagate information without moving charge, reducing energy dissipation. The operation of ASL devices is based on the following principles:

1. **Spin Injection:** A spin-polarized current is injected into a non-magnetic channel, creating a non-equilibrium spin population. The spin injection efficiency  $\eta$  is given by:

$$\eta = \frac{\mathbf{P} \cdot \mathbf{M}}{M_s},$$

where  $\mathbf{P}$  is the spin polarization vector and  $\mathbf{M}$  is the magnetization vector.

2. **Spin Propagation:** The spin current propagates through the channel with a spin diffusion length  $\lambda_{sd}$ , given by:

$$\lambda_{sd} = \sqrt{D\tau_{sf}},$$

where  $D$  is the diffusion coefficient and  $\tau_{sf}$  is the spin-flip relaxation time.

3. **Spin Detection:** The spin current is detected at the output terminal, where it exerts a torque on a magnetic layer, like the STT effect in MRAM. The output voltage  $V_{out}$  is proportional to the spin accumulation  $\Delta\mu$ :

$$V_{out} = \frac{\Delta\mu}{e},$$

where  $\Delta\mu$  is the difference in the chemical potential between the spin-up and spin-down electrons.

The energy dissipation in ASL devices is significantly lower than in conventional CMOS circuits because spin currents do not involve charge movement, reducing the ohmic losses. Still, challenges remain in achieving high-speed operation and integrating ASL devices with most of the existing semiconductor technologies.

#### 4.3. Quantum Information Processing

Spintronics plays a very crucial role in quantum computing in which electron spins are used as qubits. The coherent manipulation of spins using magnetic fields or spin currents enables the implementation of quantum gates. The Hamiltonian for a spin qubit in a magnetic field  $\mathbf{B}$  is:

$$H = -\gamma\mathbf{B} \cdot \mathbf{S},$$

where:

- $\gamma$  is the gyromagnetic ratio, and
- $\mathbf{S}$  is the spin operator.

For a spin-1/2 particle, the spin operator  $\mathbf{S}$  can be expressed in terms of the Pauli matrices  $\sigma$ :

$$\mathbf{S} = \frac{\hbar}{2}\sigma.$$

The Hamiltonian then becomes:

$$H = -\frac{\gamma\hbar}{2}\mathbf{B} \cdot \sigma.$$

The eigenstates of this Hamiltonian correspond to the spin-up ( $|\uparrow\rangle$ ) and spin-down ( $|\downarrow\rangle$ ) states, which form the basis for quantum information encoding. The energy difference between these states is given by:

$$\Delta E = \gamma \hbar |\mathbf{B}|.$$

In addition to magnetic fields, spin currents can also be used to manipulate qubits. The interaction between a spin current  $\mathbf{J}_s$  and a qubit is described by the spin-transfer torque Hamiltonian:

$$H_{STT} = \frac{\hbar}{2e} \mathbf{J}_s \cdot \boldsymbol{\sigma}.$$

This interaction enables the implementation of quantum gates, such as the Pauli-X gate (spin flip) and the Pauli-Z gate (phase shift). The fidelity of these gates depends on the coherence time  $T_2$  of the qubit, which is limited by spin relaxation and dephasing processes.

Spintronic qubits are being explored for their potential to achieve fault-tolerant quantum computing. Majorana fermions, which can be realized in topological insulators, are particularly promising for this purpose because of their non-Abelian statistics and robustness against local perturbations.

## 5. Challenges in Spintronics

### 5.1. Efficient Spin Injection and Detection

One of the major challenges in spintronics is the efficient injection and detection of spin currents. Although heavy metals such as Pt and Ta are effective in generating spin currents, their integration with existing semiconductor technologies remains a challenge. Moreover, the detection of spin currents often requires complex experimental setups, which can limit the practicality of spintronic devices.

### 5.2. Long-Range Spin Transport

Another challenge is to achieve long-range spin transport without significant losses. Spin currents can be easily scattered by impurities and defects in the material, leading to spin relaxation and loss of coherence. Developing materials with low spin relaxation rates and high spin conductivity is crucial for the advancement of spintronics.

### 5.3. Integration with Existing Technologies

Integrating spintronic devices with existing semiconductor technologies is a significant hurdle. Although spintronic memory devices such as MRAM have been successfully commercialized, the integration of spin-based logic circuits with conventional CMOS technology remains a challenge. Future research is focused on developing hybrid devices that combine the best of both worlds.

## 6. Future Directions

### 6.1. New Materials with Strong Spin-Orbit Coupling

Future research in spintronics is focused on discovering new materials with strong spin-orbit coupling, which can facilitate more efficient generation and detection of spin currents. Materials such as TMDs and Weyl semimetals are being explored for their potential in spintronics applications.

### 6.2. Improved Spin Current Generation and Detection Techniques

Improving the techniques for generating and detecting spin currents is another key area of research. This includes developing new methods for spin injection, such as using topological insulators or ferromagnetic insulators, and improving the sensitivity of spin current detectors.

### 6.3. Hybrid Spintronic-Electronic Devices

The development of hybrid devices that combine spintronic and electronic components is a promising direction for future research. These devices could leverage the advantages of both technologies, such as the low power consumption of spintronics and the high speed of conventional electronics.

## 7. Conclusions

Spintronics represents a transformative approach to electronics, offering new possibilities for low-power memory, logic, and quantum computing. Although significant progress has been made in understanding spin currents and developing spintronic materials and devices, challenges remain in integrating these technologies with existing semiconductor platforms. Future research in materials science, device engineering, and hybrid technologies will continue to drive innovation in this field, bringing spintronics closer to practical realization.

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