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ADVANCEMENTS AND APPLICATIONS IN SEMICONDUCTOR SPINTRONICS: HARNESSING ELECTRON SPIN FOR NEXT-GENERATION DEVICES

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Research Paper

Abstract: *Today's semiconductor devices use the charges of electrons and holes for tasks like light emission and signal processing. Semiconductor spintronics, a newer field, aims to exploit the spin of charge carriers to advance technologies like magnetic lasers, sensors, and transistors. Spintronics could enable the creation of memory, sensing, and logic devices with capabilities that charge-based devices can't match. This work explores the progress made with spintronic materials and devices, their current uses, and what the future might hold. A key feature of emerging spintronic logic devices is their ability to generate highly spin-polarized currents in two- and three-terminal tunnel junctions, which can lead to devices that consume much less power than traditional charge-based ones. Recent advancements in material engineering give hope for the rapid development and deployment of these new spintronic technologies.*

Keywords: *Spintronics, MRAM, Spin LED, MTJ, Spin Valve, Electron Spin, Magnetic Sensors*

1. Introduction

The field of magnetics has greatly advanced due to the application of nanofabrication techniques developed within the semiconductor industry, including electron-beam lithography and argon-ion milling, which have been instrumental in the development of microscale and nano based devices and systems. However, these fields possess distinct benefits and drawbacks, as illustrated in Figure 1. A notable case of a magnetic device that leverages the spin quantum number is the hard disk drive (HDD), first created in 1956 by IBM. As of 2018, the global market for HDDs was valued at approximately $11 billion, with 376 million units shipped that year (Statista, 2024b). Magnetic field sensors represent another application area, with a

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market revenue reaching significant figures in 2018 (Solaris Market Research Analysis, 2022). Conversely, the semiconductor device sector boasted a significantly larger market, valued at about $469 billion in 2018 (Statista, 2024a). This field traces its origins to Lilienfeld's proposals and was demonstrated by the creation of the transistor in 1947 by Bell Laboratories (Arns, 1998; Brinkman et al., 1997).

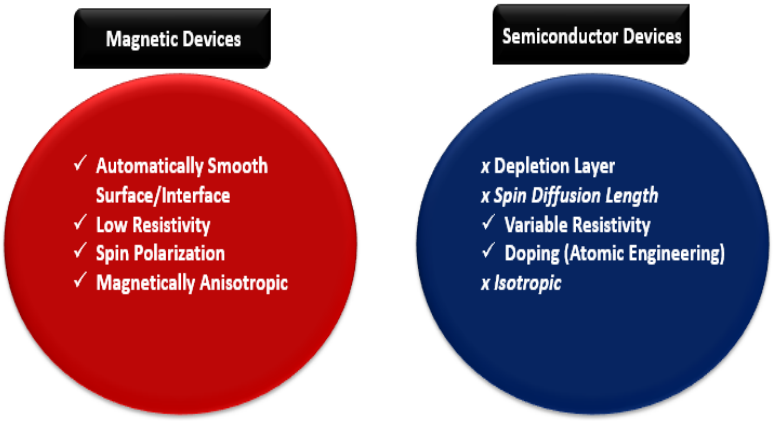

Figure 1: Comparison between Magnetic and Semiconductor Devices

Today's leading technologies have paved the way for the development of data storage solutions and the silicon integrated circuit industry. According to Moore's law, the number of transistors on an integrated circuit approximately doubles every 18 months (Zinovieva, 2020). For instance, a typical desktop computer today can store around 40GB of data, a significant increase from the 1GB capacity per disk back in 1995, thanks to advancements in magnetic hard disk drive technology. The overall bit density of a magnetic head has been increasing by 60–100% annually since 1991. As a result, the charge of electrons or holes has become a critical factor. Given that spin is considered the primary source of magnetic moments, it is the key parameter when it comes to magnetic data storage (Chappert et al., 2007).

Integrated circuits (ICs) are known for their high-speed signal processing and exceptional reliability. However, their memory components are volatile, meaning it can store data as DRAMs and lose information when the power is turned off (Jacob et al., 2010). In contrast, magnetic memory devices are non-volatile because they utilize ferromagnetic materials. The emerging field of spin transfer electronics exploits the spin of charge carriers in semiconductors to develop low-power devices, such as spin transistors, which are particularly suitable for battery-operated mobile applications (Chen et al., 2016). These devices combine photonic, electrical, and magnetic components with high-speed, non-volatile memory to generate optical emitters capable of encoding information (González et al., 2024).

Of late, electronic devices have been miniaturized to such an extent that quantum effects are starting to impact their performance. According to some industry forecasts, this physical limitation could become commercially significant as soon as 2005 (Daim et al., 2006). However, by integrating one of these quantum effects—electron spin—into device design, spin electronics (or spintronics) presents a potential pathway to maintain and even enhance the remarkable advancements in the capacity and speed of integrated circuits, along with numerous other benefits (Dieny et al., 2020).

Spintronics is a new technology that has made Moore's Law more general, and companies are now trying to go beyond its limits (Holt, 2016). Existing electrical systems can be replaced by a new one if it lowers the cost of massive integration (VLSI) in any way, like by making it smaller, faster, or using less power. Luckily, spintronics makes heat escape much less of a problem. In charge-based devices, going from logic "0" to logic "1" needs a change in the amount of charge in the active area of the device (Joshi, 2016). This makes current flow from the source (S) to the drain (D). Because charge is a scalar number and logic states depend on whether charge is present or absent, this feature of charge-based electronics makes it hard to lower power (or heat) dissipation.

Spin, on the other hand, is a pseudovector quantity that has a set magnitude of $h/4\pi$ and a variable polarisation. An electron can be in more than one state when it is in a magnetic field, but in digital systems, it only needs to be in two states: 0 and 1. These two states are eigenstates that can be shown by spin polarisation that is parallel to the magnetic field and antiparallel to it. These states represent logic 1 and logic 0, respectively. To go from one state to another, the polarisation of the spin is changed without changing the flow of current, as is the case in hybrid spintronics. This method can save a lot of energy. A certain amount of energy is still lost during the spin flip, but only about gμBB. Here, g is the Lande factor, μB is the Bohr magneton, and B is the magnetic field needed to keep the spin polarisation bistable. Taking away B can drop the term g¼BB, but it might also make random bit flips happen more often. To some extent, these bit flip mistakes can be fixed with error-correcting codes (Knill, 2005; Trieu, 2010).

Spintronics is a key technology for the next generation and holds significant promise. It offers two major future prospects: zero-emission energy and the potential replacement of CMOS technology (Haruyama, 2013). The first prospect suggests that electron spin currents do not transmit or emit heat, which means that large-scale integration circuits, personal computers, and any systems using them can operate without heat issues (Demidov et al., 2012). This is a significant advantage. Additionally, as CMOS FETs approach their limits in terms of integration and functionality, there is a need for superior devices to ensure continued technological progress. Despite the challenges posed by various materials and technologies, achieving this goal remains a work in progress (González et al., 2024). There is a growing demand for spintronic devices based on specific concepts. For example, spin flipping can be utilized to create extremely fast switching devices, surpassing the speed of LSIs and CMOS FETs.

1.1 Metal based Spintronics

1.1.1 Magnetoresistive Devices

In 1994, it was demonstrated that when a thin insulator separates two magnetic metals, they can exhibit significant tunnel magnetoresistance (TMR) even at room temperature (Moodera, 1995). Devices like giant magnetoresistance (GMR) and TMR rely on changes in electrical resistance due to magnetic field variations, forming the basis for many spintronic applications (Inoue, 2014).

1.1.2 Spin-Valves and Magnetic Tunnel Junctions (MTJs)

The discovery of giant magnetoresistance in magnetic multilayers in 1988 led to its adoption as a standard technique in the read heads of modern hard disk drives (Coey, 2020). Today, this technology, known as magnetic tunnel junction (MTJ), is recommended for use in magnetic random-access memory (MRAM) cells. These structures consist of alternating layers of ferromagnetic and non-magnetic materials, with MTJs including a thin insulating barrier that allows for tunnelling effects, enhancing their functionality in memory devices (Zhang et al., 2021).

1.1.3 Spin-Transfer Torque (STT) Devices

These devices utilize spin-polarized currents to switch the magnetization of a ferromagnetic layer, which is a principle used in advanced memory technologies like STT-MRAM (Liu et al., 2024). To advance MRAM technology beyond gigabit scales, several challenging device-level issues must be addressed. Some of these challenges are being tackled with the introduction of MgO-barrier MTJ technology. MRAM doesn't lose its state, it is used not only for memory but also as a part of programmable logic-in-memory systems. This method could potentially get around the current memory speed problems (Kimura et al., 2004).

1.2 Semiconductor Devices based on Spintronics

In semiconductors, spintronics exploits both the charge and spin of electrons to create advanced functionalities that go beyond traditional electronics. Here's an in-depth look at the key aspects of spintronics in semiconductors:

1.2.1 Generating Spin Polarization

In nonmagnetic semiconductors, spin polarization can be achieved in a few different ways. One common method is electrical spin injection, where spin-polarized electrons are introduced into the semiconductor through ferromagnetic contacts. Another method involves using circularly polarized light to induce spin polarization optically. Both techniques have their own advantages and applications in various spintronic devices (González et al., 2024).

1.2.2 Quantum Dots and Spin Interactions

Quantum dots present a fascinating scenario where the interaction between electron spins becomes significant even without the presence of magnetic ions. The spin-dependent exchange interactions in these quantum dots can lead to unique spintronic behaviours (Abdelsalam & Zhang, 2023). Moreover, when magnetic ions like manganese (Mn) are introduced into semiconductors such as InAs and GaAs, the interaction between the magnetic ions' electrons and the semiconductor's band carriers can induce hole-mediated ferromagnetism (Aspegren et al., 2024). This integration explore new spin-dependent processes in semiconductor heterostructures.

1.2.3 Integrating Ferromagnetism with Semiconductors

It is possible to combine ferromagnetic properties with nonmagnetic semiconductor heterostructures by doping semiconductors with magnetic ions (Lee, 2023). This opens up new avenues for developing spintronic devices that leverage both electrical and magnetic properties. Additionally, using an insulating-gate field-effect transistor to control carrier concentration, can reversibly switch the ferromagnetic phase transition and coercive force on and off. This electrical control of ferromagnetism in semiconductors offers a versatile approach to designing spintronic devices (Litvinov, 2024).

1.2.4 Spintronic Devices and Low Current Densities

One of the promising aspects of spintronics in semiconductors is the potential for low-current-density applications. For instance, current-induced magnetization switching (CIMS) has been observed in semiconductor nano-pillars, where either magnetization rotation or domain wall motion is induced by current (L. Guo et al., 2024). These effects can be harnessed in spintronic devices that require lower power consumption compared to their metallic counterparts.

1.2.5 Room-Temperature Ferromagnetism

A key challenge and opportunity in the field is achieving ferromagnetic semiconductors that operate well above room temperature. Success in this area could significantly enhance the practicality and integration of spintronic devices into everyday technology. Ferromagnetic semiconductors with high transition temperatures could facilitate robust magnetization switching and other spin-related effects, making them invaluable for future spintronic applications (Amin et al., 2024). These developments in semiconductor spintronics not only promise new functionalities and improved efficiencies but also align well with existing semiconductor technologies, paving the way for innovative, next-generation electronic devices (Naziba et al., 2024). In semiconductors, the manipulation of spin polarization and the associated spin degree of freedom can be accomplished through various methods. For nonmagnetic semiconductors, spin polarization can be induced either through the application of electrical spin injection or by using circularly polarized light (Flatte, 2001; Huang & Photong, 2023; Kikkawa & Awschalom, 1998). In contrast, within quantum dots, the spin-dependent nature of the exchange interaction between electrons continues to be significant, even in the absence of magnetic ions (Žutić et al., 2002).

Another approach involves incorporating transition metal ions to create an exchange interaction between these magnetic ions and the semiconductor's band carriers. For example, doping InAs and GaAs with Mn has been demonstrated to induce ferromagnetism mediated by holes, allowing for the combination of ferromagnetic properties with nonmagnetic heterostructures (Yamanouchi et al., 2004). This development facilitates the exploration of spin-dependent phenomena within semiconductors. By designing an insulating-gate field-effect transistor and adjusting the carrier concentration, researchers can reversibly control both the ferromagnetic phase transition and coercive force. These devices, which function at significantly lower current densities compared to metallic structures, exhibit current-induced domain wall motion in nano-pillars, manifesting as either magnetization rotation or domain wall movement (Yamanouchi et al., 2004). As the transition temperatures of these materials increase beyond room temperature, ferromagnetic semiconductors could become valuable for magnetization switching and various spintronic applications due to their compatibility with semiconductor technology.

2. Choosing Material for Spintronic and their Properties

2.1 Ferromagnetic Metals:

Materials like iron (Fe), cobalt (Co), and nickel (Ni) are commonly used in spintronics for their strong magnetic properties and ability to maintain spin polarization (Y. Guo et al., 2024).

2.2 Non-Magnetic Metals:

Metals such as copper (Cu) and gold (Au) are essential in spintronics for their role in facilitating spin transport without significant scattering, acting as effective spin channels (Parkin, 2004).

2.3 Heusler Alloys and Half-Metals:

These materials offer unique properties, such as high spin polarization, which are highly desirable in spintronic applications. They enhance device performance due to their specialized magnetic properties (Parkin, 2004). Two important things must be thought about when choosing the best materials for semiconductor spintronics. First, it is important to ensure that the ferromagnetism temperature is as high as possible, ideally above 300 K (Munekata, 1989). Additionally, having a well-established technological base for the material is highly beneficial. Much of the research has focused on materials like (Ga, Mn)As and (In, Mn)As (Jungwirth et al., 2014). These materials play a crucial role in multiple industries, such as high-speed digital electronics (GaAs), magnetic sensors (InAs), lasers, and infrared LEDs. For single-phase materials fabricated using molecular beam epitaxy (MBE), the highest recorded Curie temperatures are 110 K for GaMnAs and 35 K for InMnAs. Ternary alloys, such as 0.93Mn0.07As (In0.5Ga0.5), also exhibit relatively low Curie temperatures, approximately 110 K (Kohda et al., 2001).

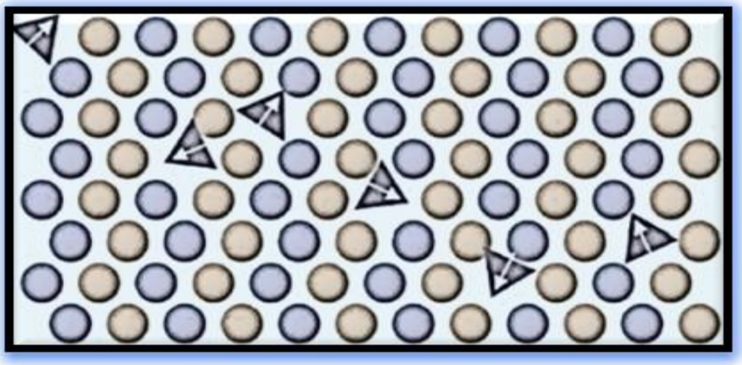

Figure 2: High Concentrations of Randomly Distributed Magnetic Impurities, Such as Mn, within a Semiconductor Matrix can Exhibit Insulating Behaviour.

For effective development of spintronic devices, several key factors must be addressed beyond just the electrical injection of spin-polarized carriers. These include the capability to detect and collect spin-polarized carriers, manage their transport through techniques such as gate biasing in transistors, and achieve high transmission efficiency in the conducting oxide or semiconductor host material

(Ziese, 2001). A thorough investigation into how spin current influences switching in magnetic heterostructures is essential for advancing these devices. Moreover, the control of spin-orbit interaction within a quantum well semiconductor via gate voltage (Parkin, 2004) could, when paired with the anticipated low power requirements of spintronic devices, facilitate extremely high memory element densities.

3. Spintronics Fundamentals

3.1 Spin Injection and Detection

This involves injecting spin-polarized electrons from a ferromagnetic material into a non-magnetic material and detecting these spins using spin-sensitive techniques like magnetoresistance measurements (Roca & Kamiya, 2024).

3.2 Spin Relaxation and Spin Diffusion

These terms describe how spin orientation in electrons decays over time and distance. Understanding these processes is crucial for designing effective spintronic devices, as they impact the efficiency of spin transport (Sverdlov & Selberherr, 2024).

3.3 Spin-Orbit Coupling

In heavy metals, the interaction between an electron's spin and its orbital motion can significantly affect spin transport and manipulation, making spin-orbit coupling a key factor in spintronics (González et al., 2024).

The rapid downsizing of semiconductor device features significantly impacts processing power and speeds up integrated circuits. The effective application of Moore's law to MOSFET miniaturization has been supported by ongoing technological advancements. Notably, Intel's 32-nm process for MOSFETs has introduced new high-k dielectric and metal gate technologies, marking a significant step forward. Despite exploring faster materials than silicon, silicon is expected to remain the primary channel material for MOSFETs following the 22-nm technology node (Ho, 2006; Kanchana, 2022; Vosko et al., 1980). However, there are growing concerns that the semiconductor industry's scaling might be nearing its fundamental limits. To enhance CMOS device performance, innovative techniques and creative approaches are necessary. Among the most promising future developments is the use of strain to improve mobility and boost device speed (Vosko et al., 1980). Multigate device topologies, which offer better electrostatic channel control and reduced short-channel effects, are also on the horizon. A multigate MOSFET design is anticipated to emerge during the 16-nm technology phase (Wang et al., 2023). By integrating strain engineering, multigate MOSFETs are expected to offer an optimal solution for minimizing power consumption, enhancing channel management, and reducing leakage currents.

3.4 Spintronics Physics

Spintronics, or spin-electronics, focuses on polarizing electrons and manipulating their spin using an external magnetic field. This approach manages electric current through these polarized electrons. The goal of spintronics is to create semiconductors with magnetically controlled properties, significantly enhancing the functionality and versatility of future electronic devices (Bhowmik, 2024). Applications of electron spin characteristics include magnetic memory and magnetic recording (both reading and writing), as well as advancements in ferromagnetic semiconductor technology (González et al., 2024). New spintronic devices with unique electrical and optical properties may emerge, potentially operating above room temperature.

The field of electronics was notably advanced by the invention of the Giant Magnetoresistance (GMR) effect in the late 1980s (Coey & Mazaleyrat, 2023). This effect involves a significant change in a material's resistance when its electrons are aligned by a magnetic field. Spintronics utilizes a different property of electrons—spin—to store and transmit data. An electron's spin can be oriented either up or down, akin to a compass needle. In nonmagnetic materials, electron spins are typically random, leading to no net effect. However, aligning these spins can be achieved by applying an external magnetic field. This effect was initially demonstrated with a device composed of alternating layers of magnetic and nonmagnetic conducting materials. Referred to as a "spin valve," this device changes its electrical resistance when the spins align from an all-up to an all-down configuration in response to a magnetic field, thereby regulating the flow of electrical current through it.

3.5 The Effect of Spin Hall

For spintronics to operate effectively, it's crucial to control spin-polarized electrons within a conductor. One key mechanism that enables this is the spin Hall effect. In the conventional Hall effect, when a magnetic field is applied perpendicular to the direction of current flow, it generates a voltage across the conductor that is perpendicular to both the current and the magnetic field. This is because the magnetic field applies a Lorentz force to the flowing electrons, which makes them deflect to one side of the wire. This makes a voltage difference (Zheng et al., 2024).

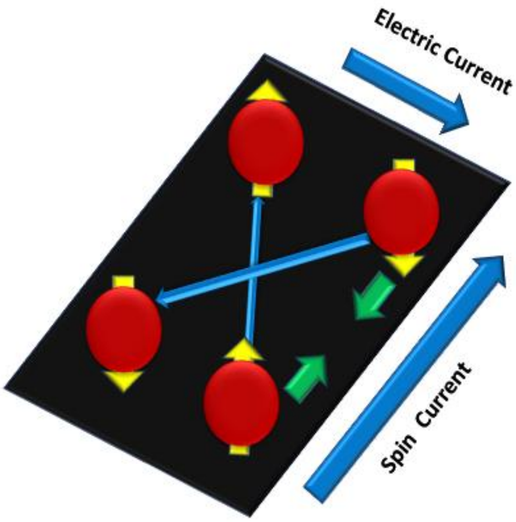

Figure 3: The Spin Hall Effect

3.6 Spin Transfer to Semiconductors

Future advancements in spintronics could reduce the reliance of current information technology on electron charge. As per Moore's Law, which predicts that electrical components will continue to shrink until they reach atomic scales, the spin degree of freedom in electrons has emerged as a promising alternative to address challenges in the microelectronics sector. Recently, researchers (Alabidi et al., 2023; Khalili Amiri et al., 2024; Meng et al., 2023) achieved a significant milestone by successfully introducing spin-polarized currents from ferromagnets into silicon. Since silicon lacks nuclear spin and thus experiences minimal hyperfine interactions, electrons in the semiconductor maintain their spin state relatively well.

4. Electronic Apps

For instance, computer hard drives already utilize the unique properties of certain materials. They store data by arranging microscopic patches of chromium oxides or magnetic iron on the disk. A "read head," which rotates beneath the disk, detects data by monitoring minute changes in the magnetic field. The head's magnetoresistance, or electrical resistance, changes because of this process. MRAM has been developed using MTJ, a concept derived from the recent discovery of TMR (Kossar et al., 2024). In this technology, an insulating metal oxide layer is sandwiched via two layers of magnetic. Unlike GMR devices, or "spin valves," where electrons can easily move between layers, TMR devices require the layers to be more magnetized to enable electron tunnelling. Spintronic devices, which combine the advantages of semiconductors and magnetic materials, are expected to offer high speed, stability, and low power consumption. They are more durable, versatile, and compact—measuring under 100 nanometres—when compared to conventional silicon-based chips and circuit components. The potential market for these devices is estimated to be worth hundreds of billions.

4.1 Spin Transistor

Suprio Datt and Biswajit Das came up with the idea of a spin transistor, which works by using a gate voltage to change the spin direction of electrons. There are ferromagnetic electrodes, a semiconductor channel with an electron layer, and a gate electrode that is connected to the semiconductor that make up a spin-FET. Metals that are ferromagnetic (FM) are used as the source and drain electrodes. Spin-polarized electrons are injected from the FM source electrodes into the semiconductor channels, where they begin to align their spins. The gate electrode applies an electric field to regulate this spin orientation. If the spin alignment of the electron channels matches that of the FM drain electrode, electrons can flow through to the drain electrode (Jangra & Duhan, 2024). Conversely, if the spin orientation is mismatched, electrons are blocked from reaching the drain electrode. This mechanism allows for the manipulation of electron spin orientation via the gate electrode as shown in Figure 4.

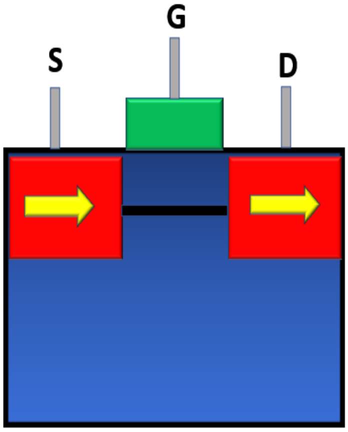

Figure 4: Schematic Diagrams of Classical Spin FETs [G: Gate, D: Drain, S: Source]

4.2 BJT Spin (Magnetic)

In a magnetic transistor, magnetized ferromagnetic layers function similarly to N-type and P-type semiconductors. When the ferromagnetic layers are aligned parallel, significant current can flow through them, much like in a spin-valve. However, if the central layer in a three-layer structure is misaligned with the two outer layers, it creates substantial overall resistance, resulting in a limited current flow (Raj et al., 2024). A magnetic transistor could potentially operate with on and off states based on the orientation of the central magnetized layer. If two outer layers are fixed and the central layer can be adjusted by an external magnetic field, this setup allows for such switching. This type of magnetic (or spin) transistor could be a viable option for implementing spin-based logic.

4.3 Magneto Resistance Spin Valve that Spin

Spin valves are a kind of spintronic technology that are used a lot in business today. Most modern hard disk drives use spin-valve technology to read spinning platters. Essentially, a spin valve functions like a spin switch, activated by external magnetic fields. It consists of two ferromagnetic layers separated by a very thin non-ferromagnetic layer. When the ferromagnetic layers are aligned parallel, electrons can flow easily between them (Barman et al. 2024; Segura et al., 2020; Yadav et al., 2024). Conversely, when the layers are aligned anti-parallel, the electron flow is restricted. The operation of spin valves is governed entirely by quantum mechanical principles.

4.4 LEDs that spin

Recent advancements have shown that effective spin injection is achievable across various semiconductor tunnel diode configurations. This has been demonstrated through two primary methods: using a spin-polarized diluted magnetic semiconductor (DMS) as the injector and utilizing a paramagnetic semiconductor as a spin filter under a strong magnetic field. In these setups, spin-polarized holes are introduced into a quantum well, where they recombine with unpolarized carriers from the opposite side. This interaction results in light that is left-circularly polarized, as indicated by electroluminescence spectra (Dashlkhagvaa & Orosoo, 2023; Kohda et al., 2001; Nishikawa, 2024). Furthermore, integrating transition metal impurities into one of the contact layers of an LED can render the device ferromagnetic, thus simplifying its design and operation.

5. Fabrication and Characterization Techniques

5.1 Thin Film Deposition

Techniques such as sputtering and MBE are used to create the high-quality metallic thin films needed for spintronic devices.

5.2 Characterization Methods

Tools like magnetometry, electron microscopy, and spin-polarized spectroscopy are essential for analysing the properties and behaviour of spintronic materials.

6. Challenges and Limitations

6.1 Scalability and Integration

Integrating spintronic devices with existing semiconductor technologies presents challenges, particularly in terms of manufacturing processes and scalability.

6.2 Thermal Stability

Spintronic devices must perform reliably across a range of temperatures, requiring materials and designs that maintain stability under thermal stress.

6.3 Material Defects and Impurities

Defects and impurities can significantly impact the spin transport properties of materials, posing a challenge to maintaining device performance and consistency.

7. Applications

7.1 Data Storage

Spintronics has already revolutionized data storage with technologies like HDDs and MRAM, which offer high density and non-volatile storage solutions.

7.2 Quantum Computing

The potential for using electron spins as qubits in quantum computing could lead to significant advancements in this emerging field.

7.3 Spintronics in Sensing

Spintronic devices are also being used in sensors, including those for magnetic fields and biosensing applications, taking advantage of their sensitivity to spin-dependent phenomena.

8. Future Perspective

Spintronics is poised to become a mainstream technology in microelectronics. The industry's transition to spintronics was highlighted by the initiation of magnetic memory production at leading microelectronic foundries in 2018. With this critical development underway, it can be expected to be continued progress and the introduction of new applications leveraging spintronic phenomena and devices. Spintronics holds tremendous promise as a key technology for the next generation (Haruyama, 2013). Its future lies in two main areas: zero-emission energy and replacing CMOS technology. The first advantage is that electron spin currents do not transmit or emit heat, effectively eliminating heat issues in large-scale integrated circuits, personal computers, and any system that uses them. From another perspective, developing devices that surpass CMOS FETs—which are nearing their limits in integration and functionality—is crucial for advancing technology. Although this goal has not yet been achieved due to challenges with various materials and technologies, the potential benefits are significant for the future of humanity. To advance spintronic device applications, the following areas should be explored for new directions:

8.1 Low-Temperature Spintronic Devices

Enhance spintronic devices for efficient performance in low-temperature environments to advance quantum engineering and large-scale computing applications.

8.2 Artificial Neurons and Synapses

Develop spintronic-based artificial neurons and synapses for applications in artificial intelligence.

8.3 Low-Power Electronics

Utilize the non-volatility of magnetic devices and electric field writing to develop low-power electronics. This involves creating materials with a higher VCMA coefficient, integrating room-temperature multiferroic materials with large TMR in MTJs, or finding other electric field-sensitive materials like magnetic semiconductors that operate at room temperature.

8.4 Innovative Circuit Architecture

Design novel circuit architectures that fully leverage spintronic phenomena, materials, and devices, such as those used in memory computing or normally-off/instant-on systems.

8.5 Efficient Read-Out

Explore low-power read-out methods using spin-orbit phenomena instead of relying on tunnel magnetoresistance.

8.6 Unconventional Computing

Explore novel computing methods utilizing spintronic devices, with a focus on stochastic computing techniques.

8.7 3D Spintronic Devices

Investigate three-dimensional spintronic architectures aimed at advancing high-density memory and storage solutions.

8.8 Photonics and Spintronics Integration

Investigate the integration of photonics with nanomagnetic and spintronic technologies, with particular emphasis on optical interconnects for electronic applications and all-optical writing techniques in data storage systems.

8.9 Advanced Magnetic Field Sensors

Create new magnetic field sensors that are more sensitive, don't change as much with temperature, and can sense a wider range of field dynamics. These sensors can be used in many areas, from position encoders to medical tests and HDD read-heads.

9. Conclusion

To keep up with the fast pace of discoveries, ongoing progress is needed in several areas: shrinking optoelectronic components, advancing materials science, improving lithography techniques, refining device fabrication, and deepening our understanding of solid-state spin interactions. As researchers tackle these challenges from various perspectives, the field is making significant strides in understanding and utilizing the spin degree of freedom in semiconductors and metallic multilayers.

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