Spintronics : The Future Technology

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Abstract

Existing semiconductor technology uses the charge of electrons to perform specific functionality such as fabrication, data, and signal processing. Spintronics or spin-based electronics is a relatively new field of electronic semiconductor technology that exploits both degrees of freedom namely the spin state and the charge state of an electron for providing the potential benefits of non-volatility, increased data computation and processing, decreased heat losses, and power consumption, enhanced energy efficiency, integration with existing technology, quantum computing, DNA computing, high-density data storage, improved sensing technology compared with the existing semiconductor technology. **The word is composed of electronics and spins. It implies the spin transport electronics, assisting in the passing of information.**Thus, it seems a new boosting technology that can combat the prevailing problems in traditional semiconductor technology. This technology successfully integrates semiconductor microelectronics with magnetic device functionalities into one integrated circuit. Due to the continuous shrinking of the transistor size, we have reached the physical limit of fabrication and designing of the integrated chip. At this stage, the fabrication and other device operational processes will become challenging as the quantum effect comes into play. Thus, it is necessary to find an alternative technology and spintronic may be such technology to transfer and receive information. In this review, I will be discussing the Basics of spintronics, its history, approaches, the famous GMR effect, applications of spintronics, issues, and problems with this technology, and finally, I conclude my review with the future use and the latest research in the field of spintronics.

I. Introduction

The existing semiconductor technology uses only the charge of electrons to carry out any needed function such as data transfer, processing, computation, fabrication of CMOS and FETs, rectification, inversion, modulation, light emission, light propagation, etc. Moore's law states that the number of transistors on the integrated chip will double after every 2 years [1]. Starting with the 10KB memory (storage of Magnetic Drum memory in the 1950's) [2], we have reached the order of terabytes of storage capacity successfully because of the incessant shrinking of the transistor size. But we have reached the final limit of 1 nm or so. Now we are using only a handful of atoms to make the transistor [3]. The problems arise due to the finiteness of the speed of light, the Heisenberg uncertainty principle, and the increase in the value of resistance and decrease in the value of capacitance as miniaturization goes on [1].

Robert Colwell, director of the Microsystems Technology Office at the Defense Advanced Research Projects Agency, uses the year 2020 and 7 nm as the last process technology node. **"In reality, I expect the industry to do whatever heavy lifting is needed to push to 5 nm, even if 5 nm doesn't offer much advantage over 7 (nm), and that moves the earliest end to 2022. I think the end comes right around those nodes** [1].

At this stage, there is a high necessity for a new technology that replaces the existing semiconductor technology. The technology that uses the spin state of the electron is magnetic data storage, which drives many researchers to exploit the spin state of the electron. **Spin is a complete quantum phenomenon.** Spintronics is highly promising as a key technology for the next generation. It has the following two prospects: The first prospect is that electron spin current carry and emits no energy and no heat. This resolves the problem of heating in many devices. From the second prospect, it is a desirable subject for human life to realize devices beyond CMOS, and FETs, which are approaching their integration and operation limits. These two key aspects of the spintronic, have gained the attention of many researchers working on the semiconductor device across the world.

II. **The brief history**

The two experiments in the 1920's suggest spin as the key property of an electron along with its charge. One was the experiment that showed the existence of fine structures in the hydrogen atomic spectrum in 1920. The other was the **Stern-Gerlach Experiment**, which in 1922 that a beam of silver atoms directed through an inhomogeneous magnetic field would be forced into two beams which indicates the presence of two states of spin of an electron[4].

In 1925, Samuel Goudsmit and George Uhlenbeck made the claim that features of the hydrogen spectrum might be explained by assuming electrons act as if it has a spin [4]. They assumed that the electron has two spin states namely, spin-up $\left(\frac{1}{2}\right)$ and spin-down $\left(\frac{-1}{2}\right)$.

In 1965, Gordon Moore, Intel's co-founder, predicted that the number of transistors on a chip will double every two years[1]. That prediction which is now known as the famous Moore's Law, effectively described a trend that has continued ever since, but the end of that trend- the moment when transistors are as small as atoms, and cannot be shrunk any further- is expected as early as 2015.

The Magneto-Resistance effect is the property of a material to change the value of electrical resistance when placed in the external magnetic field. The first Magneto-Resistance effect had been observed by William Thomson in 1856 [5], but he was unable to lower the electrical resistance of anything by more than 5%.

Giant Magneto-Resistance (GMR) is a quantum mechanical magneto-resistance effect observed in multilayers composed of atleast two ferromagnetic and one non-magnetic conductive layers. Albert Fert and Peter Grunberg were awarded the noble prize in 2007 for their discovery of the Giant Magneto-resistance Effect[6]. This effect is much more highlighted than Thomson's magneto-resistance effect because, at this time, significant change is observed in the electrical resistance of the Fe/Cr multilayers.

III. Working and Types of Spintronics

Every electron has two states- spin up and spin down. In the case of ordinary materials, electron spins are randomly organized resulting in zero net spin. But in the case of ferromagnetic materials, many domains (ferromagnetic material is divided into domains. They are the regions containing the same spin state electrons.) are randomly oriented resulting in zero net spin in the whole material. When the magnetic field is applied, then all the domains will line up in saturation giving a large net spin angular momentum[7].

There are two ways in which the electron spin can be exploited, often called the types of spintronics, which are metal-based spintronics and semiconductor-based spintronics:

(*a*) <u>Metal-based Spintronics</u> - After the discovery of the GMR effect in 1988, which became the standard technology for read-heads in the hard disk drive (HDD), a large tunnel-magneto resistance (TMR) effect between two ferromagnetic layers, in which one is fixed and the other one is movable, separated by a thin insulating layer was demonstrated in 1994 [8]. This MJT (Magnetic Tunnel Junction) technology is currently being used to make MRAM (Magnetic or Magneto Resistive Random Access Memory) in computer systems. **This MRAM not only acts as a memory but as a part of reconfigurable logic-in-memory [9].**

(*b*) <u>Semiconductor-based Spintronics</u> - Semiconductor Spintronics consists of a doped silicon lattice that shows dilute ferromagnetism. It is combined with photonics and magnetics, which give various functional devices such as spin-transistors, spin-LEDs, memory devices, and optical switches. In this type of spintronics, traditional semiconductor lattice technology is combined with spintronic technology to produce a new device with satisfactory needs.

IV. Polarisation of electron spin current

Spin current or spin polarised current is the actual phenomenon that transfers the data or information utilizing the spin of the electron. Spin polarisation is the degree to which the spin, i.e., the intrinsic angular momentum, is aligned with a given direction. In this, magnetic layers as spin polarizers or analyzers govern the spin polarization via spin-orbit coupling. Due to this, the spin current is generated, which is produced by spin waves [10].

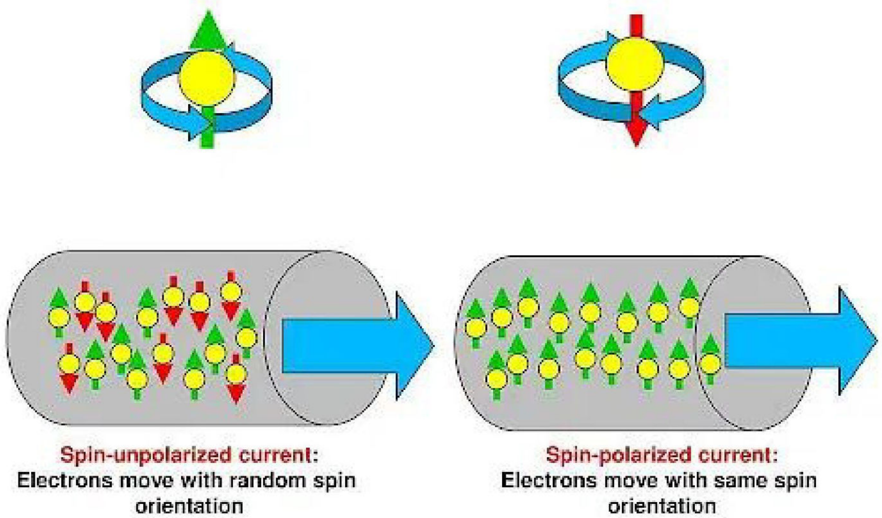

Figure 1: Types of Spin currents

V. Giant Magneto Resistance Effect (GMR)

Giant Magnetoresistance (GMR) refers to the phenomenon in which the electrical resistivity of a magnetic material changes greatly when it has an external magnetic field as compared with the absence of an external magnetic field. It is a **quantum mechanical magnetoresistance effect** observed in layered magnetic thin film (nanometers thick) structures.

(a) **Discovery of GMR effect:**

The Giant Magnetoresistance was independently discovered in 1988 by Peter Andreas Grunberg of the Yulich Research Center in Germany and by Albert Fert of the Eleventh University in Paris. They jointly won the 2007 Nobel Prize in Physics. In the initial work, Peter Andreas Grunberg's research team only studied structural materials composed of three layers of iron, chromium, and iron. Their experimental results showed that the electrical resistance value decreased by 1.5%. While Albert Fert's team studied multilayer materials made of iron and chromium, which reduced the resistance value by 50%.

Andreas Grunberg and the Yullich Research Center had a patent for giant magnetoresistance technology, and his original paper was submitted a little earlier than Fert's (Andreas Grunberg's on 31 May 1988, Fert's on 24 August 1988). But Fert's article was published earlier (Andreas Grunberg's in March 1989, Fert's in November 1988). **Fert accurately described the physical principles behind the giant magnetoresistance phenomenon, while Andreas Grunberg quickly found the importance of giant magnetoresistance in technical applications** [10].

(b) **Principle of the GMR effect:**

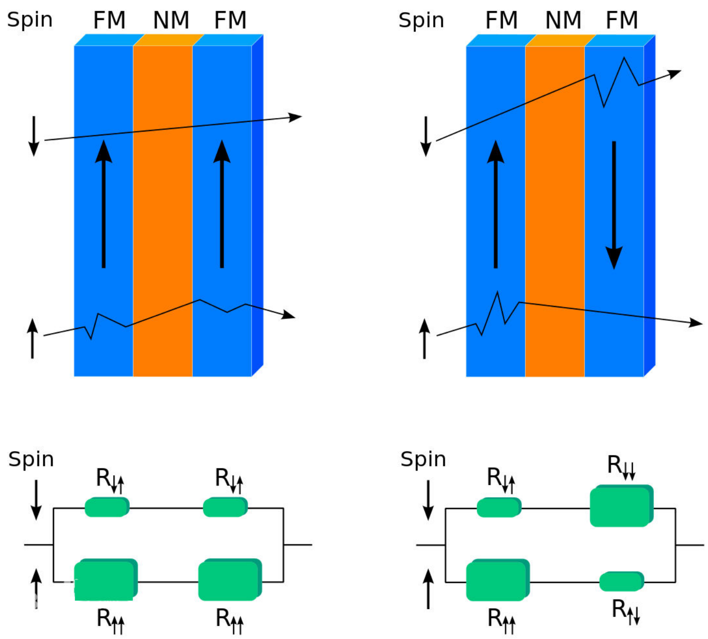

Figure 2: Diagram Of GMR effect

As shown in the above diagram, is two ferromagnetic (magnetic thin films) layers(blue) on both sides and a thin film layer of non-magnetic insulator (orange) in the middle.
In the left side diagram, both the magnetic layers have the same magnetization direction in the absence of a magnetic field, and thus, the electrons having the same spin as that of the magnetization direction of the layers will have the least scattering, accounting for the small resistance. While the electron having opposite spin results in scattering and decreasing the number of electrons passing through, hence reducing the current.
But in the right-hand side diagram, the directions are opposite, and thus both the spin states of electrons will scatter in one of the layers, thereby increasing the overall resistance.

Overall, when the magnetic moments of the ferromagnetic layers are parallel to each other, the carrier-dependent scattering is minimal and the material has the smallest resistance. When the magnetic moment of the ferromagnetic layer is anti-parallel, the spin-related scattering is the strongest and the resistance value of the material is the largest.

(*c*) **Analysis of GMR effect:**

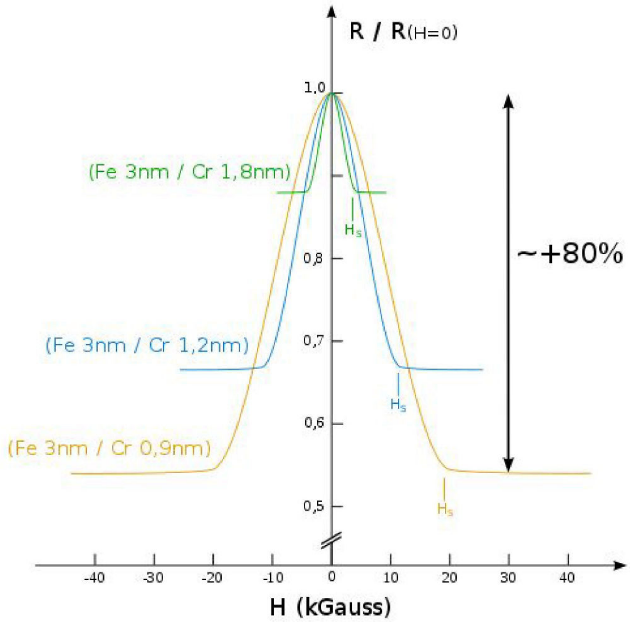

Figure 3: Resistance v/s Magnetic intensity

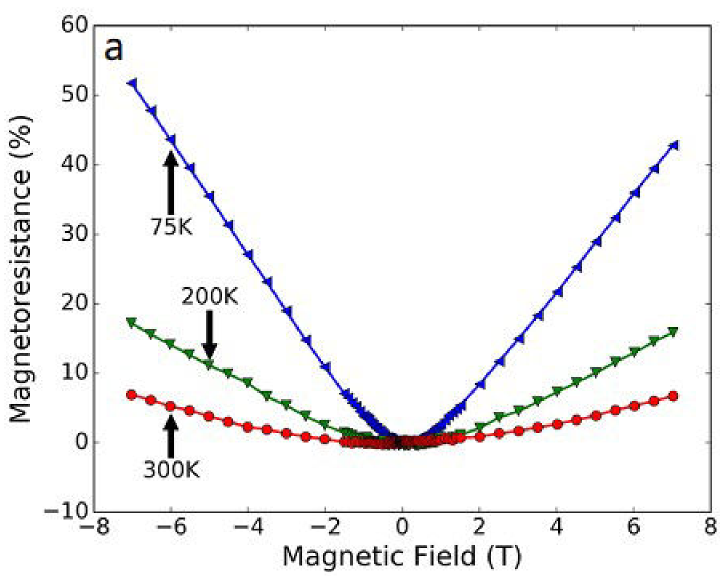

Figure 4: Percentage Magneto-Resistance

The above two figures indicate the behavior of resistance and the GMR effect with the external magnetic field. Initially, both layers are anti-parallel coupled, which minimizes the total energy. As the external magnetic field increases, the resistance gradually decreases and there is an approximate linear region. When the external magnetic field has made the magnetic field directions of the two ferromagnetic films completely parallel coupling, the magnetic field continues to increase but the resistance no longer decreases, reaching the state of magnetic saturation. **The important observation is that when the magnetic field is decreased then the curve will not follow the same trajectory as shown, but follows the different trajectory accounting for the hysteresis in the magnetoresistive material as shown in figure 5 below**.

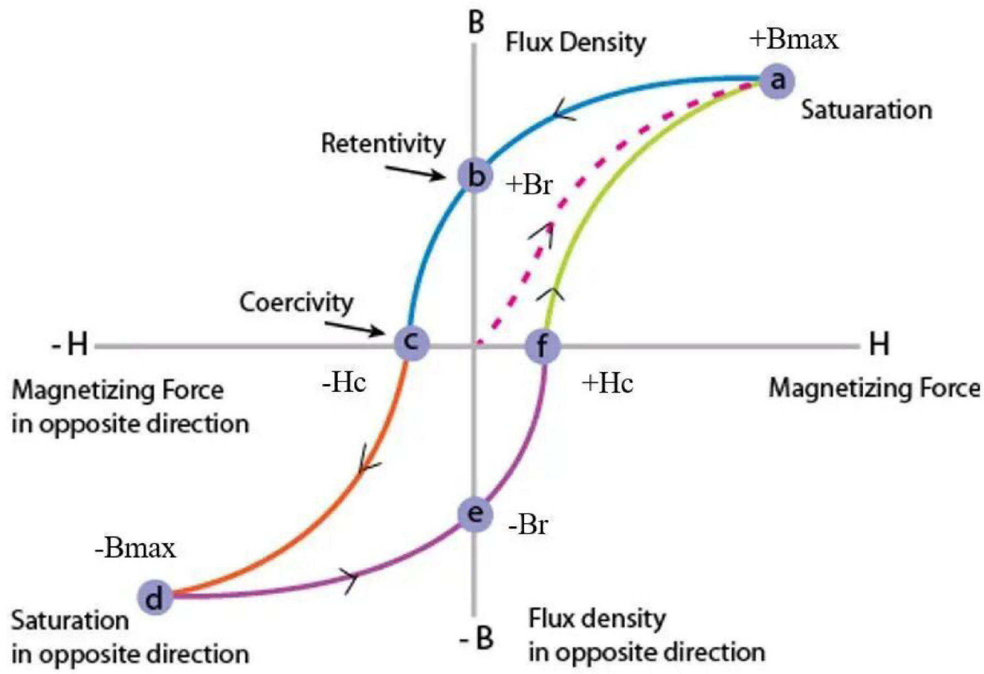

Figure 5: Hysteresis Curve

The magnetoresistance characteristics are symmetrical when the reverse magnetic field and the forward magnetic field are added. The external magnetic field changes the two layers of ferromagnetic film from anti-parallel coupling to parallel coupling and finally saturation occurs. To reach saturation, a strong magnetic field has to be applied to the system.

(*d*) **Applications of GMR effect:**

GMR effect has been extensively studied and has found numerous applications in various fields. Here are some of the notable applications of the GMR effect in the real world:

Magnetic Sensors: One of the most significant applications of GMR is in the development of magnetic sensors. GMR sensors are highly sensitive and can detect extremely weak magnetic fields. They are used in various applications such as compasses, position sensors, magnetic field measurement devices, and non-destructive testing.

Data Storage: GMR has revolutionized the field of data storage. GMR-based read heads are used in hard disk drives (HDDs) to read the magnetic patterns on the disk's surface. The GMR read heads are highly sensitive to small magnetic fields, enabling higher data densities and increased storage capacity in HDDs. GMR technology has played a crucial role in the miniaturization and advancement of magnetic storage devices.

Spintronics: Spintronics is a field that utilizes the spin of electrons in addition to their charge for information processing and storage. GMR plays a vital role in spintronics devices by enabling the detection and manipulation of spin-polarized currents. GMR-based spin valves and magnetic tunnel junctions are used in spintronic devices such as Magnetic Random-Access Memory (MRAM) and spin-based logic devices.

Other applications include those in biosensors for detecting the body balance, pH, blood pressure, and temperature. GMR effect has been utilized in MRI techniques and Nondestructive Testing(NDT) that detects defects in materials without damaging them. Magnetic readout systems used in modern days nonvolatile memory devices and the MRAM technology are all children of GMR effect.

GMR sensors found various practical use in consumer electronics, energy, and power systems, aerospace and defense, magnetic field detection magnetic field imaging, and automotive applications.

These diverse applications highlight the versatility and significance of the GMR effect in multiple industries, ranging from electronics and healthcare to automotive and aerospace. Continued advancements in GMR technology hold the potential for further innovations and improvements in these fields.

VII. Issues with the use of Spintronics Technology

While spintronics holds great promise for various applications, there are still several challenges and issues as follows:

Integration with Existing Electronics: Electronics: Integrating spintronic devices with existing electronic technologies poses a significant challenge. Traditional electronic devices are based on charge transport, while spintronic devices utilize the spin of electrons. Bridging the gap between spin-based and charge-based systems is a complex task that requires the development of efficient interfaces and interfaces that enable seamless integration of spintronic and traditional electronic components.

Fabrication and Design Complexity: Many spintronic devices rely on complex materials systems and fabrication processes. For example, creating high-quality magnetic tunnel junctions (MTJs) with precise control over their properties and interfaces can be challenging. It becomes a very challenging task to make such devices at room temperature.

Energy Consumption: Although spintronic devices have the potential to be energy-efficient, the generation, manipulation, and detection of spin currents in devices often require high currents, which can lead to increased power consumption.

Cost and Manufacturing: The cost associated with spintronic materials, fabrication processes, and equipment can be a significant hurdle for widespread adoption. Developing cost-effective manufacturing techniques and scalable processes is necessary to make spintronics more economically viable for various applications.

Spin Polarised Transport[17]: Taking both the charge and spin of an electron into account poses many intricate limitations on the design of the device. It is not clear how the spin degree of freedom will behave in transport across interfaces. This poses serious problems in the study of transport and the further fabrication process. Material inhomogeneities can also act favorably and be tailored to give the desired effect for spin-polarized transport.

Spin based Quantum Computation[17]: The most revolutionary application of spintronics comes into play when one talks about quantum computers (QC). Both the spin states of the electron are utilized in Qc as 0 and 1 base states. The major difficulties facing various QC models are achieving precise control over unitary evolutions and maintaining quantum mechanical coherence. While traditional electronic devices deal with large numbers of electrons at a time, in spin-based QC one has to be able to precisely control the spins of individual electrons.

VIII. Latest Research and the Conclusion

The spin degree of an electron has been exploited in almost every field of science and electronics, in order to improve and achieve acceptable results. There is much research going on in this technology because there is an inevitable need for such a new revolution that would meet the limitations of the well-accepted law, Moore's law. Other things include efficiency in energy consumption, high-speed computation, and importantly non-volatility and data storage.

In spite of these and that is highlighted above, there are many other research areas in which spintronics has been applied. **The development of quantum engines** for more efficient energy utilization, operation at low voltages, etc, and probing spin structures of various crystals. **Building logic gates from the spin waves** will decrease the delays in the electronic circuits which will increase the efficiency and throughput of almost all the logic used in an electronic device. More typical experiments include robust quantum point contact operation, long-distance spin transport, topological valley currents, and quenching an anti-ferromagnet into a high resistive state.

Spintronics also has various potential uses in the biological and medical fields. The ongoing research consists of improving the MRI technique using spintronics that will enhance the sensitivity, resolution, and efficiency of MRI machines, which will result in the accurate and detailed imaging of biological tissues. Biosensors can be used for detecting biomarkers, monitoring biochemical processes, and advancing medical diagnostics. Neural networks can be studied in more detail to understand the quantum spin transfer of signals across the neurons which would enhance neural interfaces.

These are just a few examples of the latest research topics and fields in spintronics. The field is interdisciplinary, combining physics, materials science, and engineering, and it continues to advance with new discoveries and applications being explored. As the field advances, it is becoming increasingly recognized for its potential to revolutionize information processing and storage.

The field of spintronics may seem complex and challenging to some due to its roots in quantum physics and chemistry. However, it is important to remember that electronics was once considered esoteric as well but is now a widely accepted and used technology that underpins modern society. Today, spintronics is a maturing field of applied science and engineering, as well as fascinating pure science in its own right. It is worth noting that spintronics is already established in one critical area of digital electronics: data storage. We should accept this new technology and give it some time to strengthen its roots.

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References:

[1] Moore's law

[2] History of Computer data Storage

[3] Status of Moore's law

[4] Pauli's Principle

[5] Magnetoresistance

[6] Giant Magneto-resistance Effect

[7] Fundamentals of Spintronics

[8] Tunnel Magneto-Resistance

[9] Spintronics Technology

[10] Spin Polarization

[11] Discovery and Principle of GMR effect

[12] MagnetoResistance with External Field

[13] Issues and Challenges in spintronics

[14] Spintronic Devices

[15] Quantum Engines

[16] Research- Probing 2D Spin structure

[17] Research-Semiconductors shine in the dark