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Spintronics: A New Nanoelectronics Adventure

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Abstract

Spintronics is a new paradigm for electronics which utilizes the electron's spin in addition to its charge for device functionality. It is a rapidly emerging field of science and technology that will most likely have a significant impact on the future of all aspects of electronics as we continue to move into the 21st century. The primary areas for potential applications are information storage, computing, and quantum information. The main objective of this paper is to present a current status of fundamentals of Spintronics including the recent advantages and well established results like MRAM, Quantum computer – only one step remain to come on Earth etc. The primary focus is on basics physical and quantum properties of electron underlying Spin mechanics, Spin polarization, Spin transport through metal and semiconductor, Spin injection etc., principal of GMR with their types and applications is also discussed in details in this paper.

Keywords

Spintronics, GMR, Spin , Quantum mechanics.

1. Introduction

The new generation of Microelectronics will profess the newly discovered devices based on electron spin, rather than electronic charge. The last half of the 20th century, it has been argued with considerable justification, could be called the microelectronics era. From the earliest transistor to the remarkably powerful microprocessor in your desktop computer, most electronic devices have employed circuits that express data as binary digits, or bits—ones and zeroes represented by the existence or absence of electric charge. Moreover, it is known that the communication in microelectronics devices takes place by flow of electric charges in binary form. This mere logic has led to multi trillion dollar industries per year whose products are omnipresent. Indeed, the relentless growth of microelectronics is often popularly summarized in Moore's Law, which holds that the numbers of transistors per square inch on integrated circuits will double every 18 months. The rapid improvement in performance and reduction in cost of computers and communications devices was fuelled by Moore's Law. Quantum effects show their presence in atomic levels whose predominance has been seen lately. It's now MORE the Moore's Law, which will lead to the end of the silicon era. For this reason and also to enhance the multi-functionality of devices (for example, carrying out processing and data storage on the same chip) investigators have been eager to exploit the electronic property of spin. In fact, the spintronics dream is a seamless integration of electronic, optoelectronic and magneto electronic multi-functionality on a single device that can perform much more than is possible with today's microelectronic devices [1].

A. History and Background

Spintronics emerged from discoveries in the 1980s concerning spin-dependent electron transport phenomena in solid-state devices. this includes the observation of spin-polarized electron injection from a ferromagnetic metal to a normal metal by Johnson and Silsbee (1985) and the discovery of giant magneto resistance independently by Albert Fert and Peter Grünberg (1988)[2]. The origins of spintronics can be traced back even further to the ferromagnetic/superconductor tunnelling experiments pioneered by Meservey and Tedrow and initial experiments on magnetic tunnel junctions by Julliere in the 1970s [3]. the use of semiconductors for spintronics can be traced back at least as far as the theoretical proposal of a spin field-effect-transistor by Datta and Das in 1990[4].

2. Electron Spin: Theory

The fundamental property of electrons is the spin angular momentum. The direction of spin can have two possible experimental outcomes, spin up and spin down. A Stern-Gerlach apparatus is used to measure the direction of spin. Electrons with different spins experience different resistance in a magnetized conductor. Giant Magneto Resistance effect in Ferromagnetic layers is then seen in this phenomenon. Magnetic read head and magnetic random access memory are two examples of devices that are based on the giant magneto resistance effect. By manipulating information qubits that spins encode, we may build super fast quantum computers.

In order to understand what spin is, we can image an electron as a charged sphere rotating with respective to itself. According to classical mechanics, such a sphere would have an angular momentum (S) associated with its rotational motion about its rotation axis. In addition, since the sphere is charged, the rotating charge will give rise to a current loop and classical magnetism tells us that there exists a magnetic moment (μ_s) associated with such a current loop. However, the above picture of a spinning sphere is an understanding aid rather than the reality, for the electron's size is so small that it would need to spin faster than the speed of light in order to have the correct values of S and μ_s[4]. Nonetheless, experiments reveal that spin angular momentum (S) and spin magnetic moment (μ_s) are real phenomena, and what we call spin is actually spin angular momentum. Like other quantities in the quantum, atomic world, spin angular momentum (S) can take only certain direction and magnitude (angular momentum is a vector with both direction and magnitude). The magnitude of spin angular momentum S is given by

$$S = \sqrt{s(s+1)}h/2 \quad (1)$$

Where ħ (h bar) is Planck's constant (h) over 2p and s is the spin quantum number, which equals to 1/2. The direction of spin is specified by the component of S along a particular axis, usually denoted as the z-axis (Fig. 1). The magnitude of this component S_z is given by,

$$S_z = \frac{m_s h}{2}, \quad (2)$$

Where the spin magnetic number m_s can be either 1/2 or -1/2. When m_s=1/2, the electron is said to "spin up", and "spin down" otherwise [5].

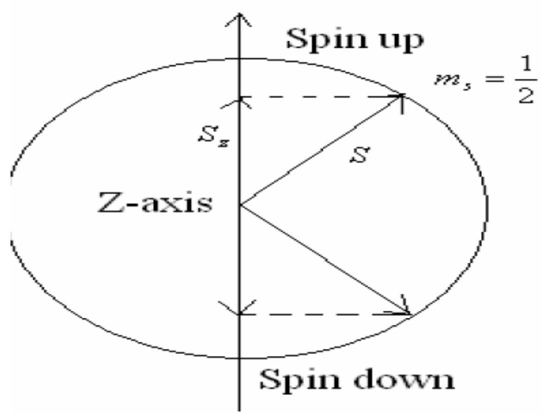

Figure 1: Spin Direction

The binary directional state of spin seems to make electron spin a perfect quantity for computer information storage and processing. One bit of information can store either one or zero. If we let spin up represent one and spin down zero (or the other way around), then one electron can carry one bit of information. However, the quantum world is probabilistic instead of deterministic. Before we make any measurements, we cannot know for sure whether an electron is spin up or down. Unless we polarized the electron, the electron is in an indefinite state, having both possibility of becoming spin up and down. Such an electron carries one quantum bit, or qubit (represents one, zero, and the superposition of both), of information [5].

A. The Logic of Spin:

1) *Long Coherence:* All the spin of electron can stay in one direction (up or down).This property is called 'Coherence'.
2) *Long Relaxation time:* Once the spin is created, then how long it is remains unchanged is given by 'Relaxation Time' (how spins are created and disappear).
3) *Low Power Consumption:* Unlike charge states, which are easily destroyed by scattering or collision with defects and impurities, spin-based-electronic systems consume less power to change spin states and therefore is more efficient than charge based electronic systems.
4) *Easy Manipulation:* Spin over charge is that spin can be easily manipulated by externally applied magnetic fields, a property already in use in magnetic storage technology.

5) *Information Carrier:* The movement of spin, like the flow of charge, can also carry information among devices [6].

3. Giant Magneto-resistance

GMR was discovered in layers iron, chrome and ferrite by Peter Grünbergs research team of the Jülich Research Centre (Germany) in 1988. Peter Grünberg owns a patent for the technology.

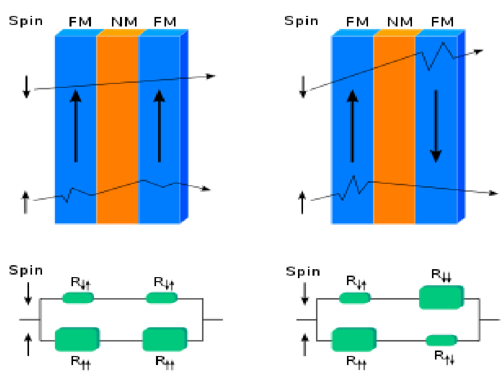

Figure 2: Simple GMR with Resistance Possessed By Electron through GMR

It was also discovered by Albert Ferts research group of the University of Paris-Sud (France) in layers ferrite and chrome. The Fert group were first to see what they thought of as a *large* effect which is why they gave the name "Giant". The Fert group was also first to explain the physics behind GMR.

A. Working:

Giant magneto resistive effect**:** The first practical application of this phenomenon is in the Giant Magneto Resistive effect (GMR). The GMR is observed in thin-film materials composed of alternate ferro-anti-ferro magnet magnetic and nonmagnetic layers as shown in figure [4]. The resistance of the material is the least when the magnetic moments in ferromagnetic layers are aligned in the same direction and highest when they are anti aligned this is because the spin-aligned currents from one layer are scattered more powerfully when they confront a layer that is magnetically arrayed in the inverse direction, creating additional resistance. But when the magnetic fields are tailored in the same direction, the spin-aligned currents pass through comfortably. Current GMR materials operate at room temperature and exhibit significant changes in resistivity when subjected to relatively small external magnetic fields. Thus they can be used as magnetic field sensors. The imposed magnetic field changes the magnetic orientation of one of the two layers, disrupting their relative orientation and thus changing the resistivity [7].

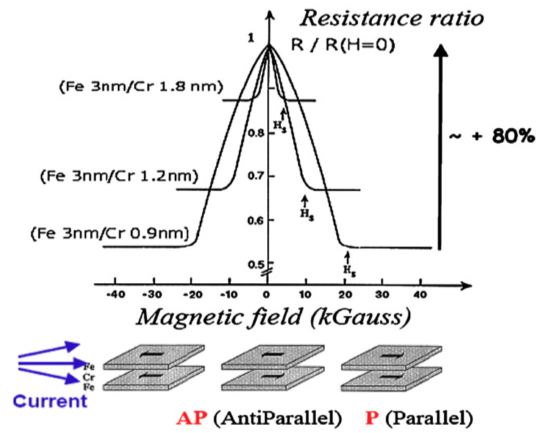

Figure 3: Resistance Ratio in Fe/Cr GMR With Different Layers Of Fe And Cr.

B. Applications:

The discovery of GMR has heavily contributed in HDD's read heads technology. From a long time AMR (Anisotropic Magneto Resistance) had been used but that resulted in lesser magneto resistance. AMR read heads was approaching its sensitivity limit with the reduction of the head and the bits dimension. Nevertheless, the introduction of the spin-valve based (GMR) read head by IBM in 1997 immediately increased growth rate for storage areal density up to 100 percent per year (Fig. 6) [8].

In more details, the spin-valve sensor is just a tri-layer film in which one layer has its magnetization pinned along on orientation. The rotation of the free layer magnetization then controls the flow of electrons by giant magneto resistance effect. The standard spin valve shows about 5~6 % magneto resistance. Therefore, the sequential introduction of the magneto resistance and spin-valve head, by providing a sensitive and scalable read technique, contributed to increase the raw HDD areal recording density by three orders of magnitude around 10 years. GMR has motivated people to develop solid state magnetic storage. The free layer magnetization of the spin valve is constrained to take only the two opposite orientation of an easy magnetization axis, arrays of patterned spin-valve elements can be used to store binary information with resistive readout. By replacing the non-magnetic metallic spacer layer of the pin valve by a thin non-magnetic insulating layer, so creating a magnetic tunnel junction (MTJ).

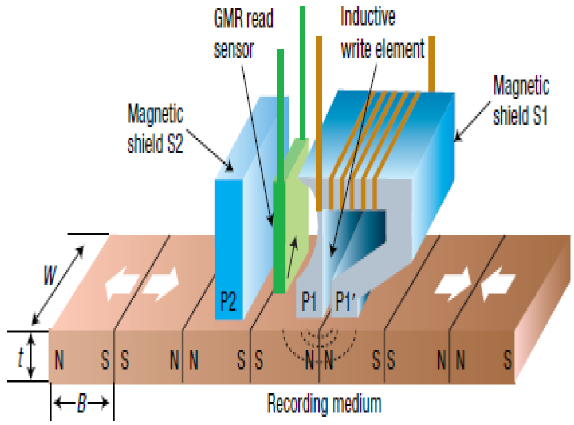

Figure 4: GMR Reading and Writing Head

In this structure, the electrons travel from one ferromagnetic layer to the other by a tunnel effect, which conserves the spin. Since the discovery of TMJ in 1994, a research of developing magnetic random access memories (MRAM) has started. The principle of MRAM is shown in Fig. 7. The binary information 0 and 1 is recorded on the two opposite orientations of the magnetization of the free layer along its easy magnetization axis. From the two cross points of the perpendicular arrays of the parallel conducting lines, MTJs are connected. Current pulses are sent through one line of each array for writing operation, and the generated magnetic field, at the crossing point of these lines, is high enough to orient the magnetization of the free layer. The addressed cell is measured for measuring the resistance between the connecting lines.

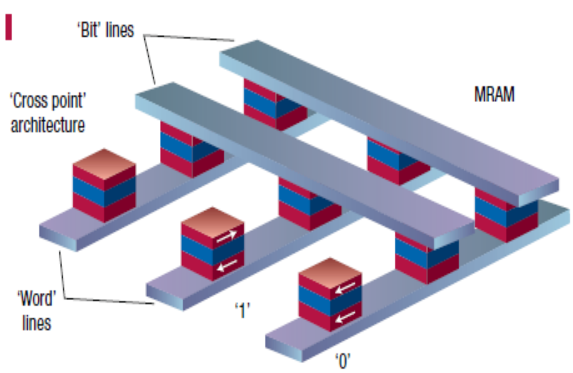

Figure 5: MRAM Reading and Writing.

4. Advantages of Spintronics

The various other advantages of Spintronics are as follows:

1) Common metals such as iron, copper, silver and aluminium can be used for implementation of Spintronics. No special semiconductor is needed.
2) To change the spin of an electron, less energy is needed. Therefore, Spintronics is more power efficient.
3) Spins don't change when power is cut off. This explains non-volatility of the memory.

A. Spin Based Quantum Computers

One of the most ambitious spintronics devices is the spin-based quantum Computer (QC) in solid-state structures. Using electron (or nuclear) spin for QC purposes is a manifestly obvious idea since a fermion with spin 1/2 is a natural and intrinsic qubit [9]. Quantum computation requires both long quantum coherence time and precise external control. Because of the requirement of very long coherence time for a QC, both nuclear spin and electron spin have been proposed as qubit in a QC. Quantum computers lead the race by their totally different and innovative algorithm harnessing the power of quantum effect in the nature. The following are the fundamental factors that throw a light on Quantum Computers:

1. Effectively More Storage

According to Quantum mechanics, an atom which has two distinct electronic states can also be prepared in coherence with the two states, as in, superposition of the two states, only if an atom is considered as a physical bit. Now if we can push the idea of superposition of numbers a bit further, then we can easily understand that as the number of quantum bits increases, power of storage grows exponentially. Any classical register of 3 bit can store in a given moment of time only one out of eight different numbers while a quantum register composed of three qubits can store in a given moment all_eight numbers in a single quantum superposition. If we keep adding qubits to the register, we increase its storage capacity exponentially i.e. three qubits has the capability to store 8 different numbers at once, four qubits has it for 16 different numbers at once, and so on; therefore we can state that L qubits has the capability to store 2^L numbers at once. And thus storage power keeps on increasing massively, with each successive addition of atom [10].

2. Extremely Faster Processing

Once a quantum register is prepared in a superposition of different numbers we can at once perform operations on all of them. For example, if qubits are atoms then suitably tuned laser pulses affect atomic electronic states and evolve initial superposition of encoded numbers into different superposition. We generate monumental amount of parallel computation even though there is one piece of quantum hardware because during such evolutions, each superposition is affected. This means that a quantum computer in *only one* computational step can perform the same mathematical operation on 2^L different input numbers encoded in coherent superposition of L qubits. In other words a quantum computer offers an enormous gain in the use of computational resources such as time and memory.

3. Highly Efficient Algorithms

Quantum algorithms have the potential to be dramatically faster than their conventional counterparts. A good example is an algorithm for searching through lists. The problem is to find a person's name in a telephone directory, given his or her phone number. If the directory contains N entries, then on average, you would have to search through N/2 entries before you find it. Grover's quantum algorithm does much better. It finds the name after searching through only $\sqrt{N}$ entries, on average. So for a directory of 10,000 names, the task would require $\sqrt{(10{,}000)} = 100$ steps, rather than 5000.[11] The algorithm works by first creating a superposition of all 10,000 entries in which each entry has the same likelihood of appearing in response to a measurement made on the system. Then, to increase the probability of a measurement producing the required entry, the superposition is subjected to a series of quantum operations that recognize the required entry and increase its chances of appearing.

5. Conclusion

In less than 20 years, we have seen spintronics increasing considerably the capacity of our hard disks, extending the hard disk technology to mobile appliances like cameras or portable multimedia players, entering the automotive industry and biomedical technology and, with TMR and spin transfer, getting ready to enter the RAM of our computers or the microwave emitters of our cell phones. The research of today on the spin transfer phenomena, on multi ferric materials, on spintronics with semiconductors, and molecular spintronics, opens fascinating new fields and is also very promising of multiple applications. Another perspective, out of the scope, should be the exploitation of the truly quantum-mechanical nature of spin and the long spin coherence time in confined geometry for quantum computing in an even more revolutionary application. “Spin much like mass and charge is an intrinsic property of electron which can be exploited in future.

Quantum computers however, will be able to examine data using spins, which has can have many different states. Next generation Quantum computers” will be able to process information much faster than the conventional microchip machines and the capacity can be increased by factor of many thousands. An inherent advantage of spintronics over electronics- the fact that magnets tend to sty magnetized – is sparking industry in replacing computer’s semiconductor based components with magnetic ones, starting with the RAM. Spintronics should take an important place in the science and technology of our century.

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