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The role of ferromagnets and antiferromagnets for spintronic memory applications and their impact in data storage

Marinos Ioannou[1,*]

[1] University of Portsmouth, School of Mathematics and Physics, Portsmouth PO1 2HE, UK

*Corresponding author (Email: up2087075@myport.ac.uk)

Abstract – The manipulation of multifunctional properties associated with ferromagnetic and antiferromagnetic materials has a great impact in information technology and digital data storage. A relatively recent field called spintronics is a promising alternative technology to store data more efficiently and to overcome obstacles that conventional electronics face. This article provides a small introduction to spintronic devices used for memory applications such as hard disk drives and MRAM, and details ways by which magnetization inside magnetic layers such as ferromagnets can be flipped. The giant magnetoresistance (GMR) effect and its successor in developing memory devices; the tunneling magnetoresistance (TMR) effect are also discussed since they are key in developing magnetic memory devices.

Keywords – Spintronic data storage; MRAM; Magnetic memories; GMR; TMR.

1. Introduction

IBM estimated in 2020 that daily, 2.5 quintillion digital data bytes are produced, and the amount of data needed for manipulation and storage grows year by year. As stated in M. Vopson's article 'The information catastrophe', the vast amount of power needed to sustain this enormous production of digital information will raise ethical and environmental concerns [1]. Scientists constantly work on the development of technologies to store data that will consume less power, will have high storage density, be non-volatile, faster, and inexpensive. Current conventional electronics depend on reducing the size of their components such as transistors and capacitors to enhance their functionality. Figure 1 shows the size and number of transistors inside a microprocessor as the years progress. However, the minimum size that the transistor will still be functional is 1nm, since after that, the reading and writing operations will be limited due to the quantum size effect [2].

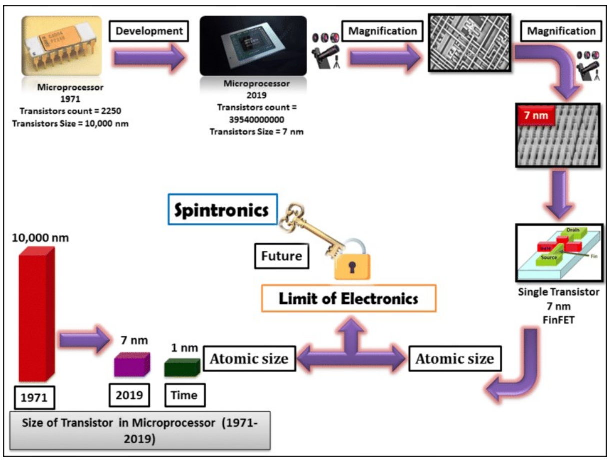

Figure 1. The development of transistors and their size evolution inside microprocessors from 1971-2019. The smallest size enabled for the transistor to work efficiently is 1nm. Image taken from [2].

Conventional electronics therefore, may reach a point that will no longer be efficient and might get replaced by another technology. Spintronics is a relatively recent and promising technology that can overcome these obstacles and can revolutionize the information world. Spintronic technology for information purposes can be found in modern devices such as Hard disk drives and MRAM. After only a period of just a couple decades, commercialization of this technology lead to huge advancements and reduction of costs for data storage. In fact, in the early 1990s, storing just 1 GB of information on a hard drive would cost about $2000, but now it costs just 3 cents [3].

2. Spintronics

As the name suggests, spintronics, short for spin electronics, is the study that exploits the spin properties of electrons for applications in technological devices [4]. It aims to create new types of devices and overcome obstacles that current traditional electronics face. Conventional electronics solely depend on the charge of electrons, while spintronics utilize both the charge and the spin of an electron. The spin provides an extra degree of freedom, representing binary information as 0 or 1, and this enables new functionalities and capabilities to be implemented for data storage and transfer [5]. This comes from the fact that the spin can be considered as a tiny magnet, having a North-South or South-North direction as shown in Figure 2.

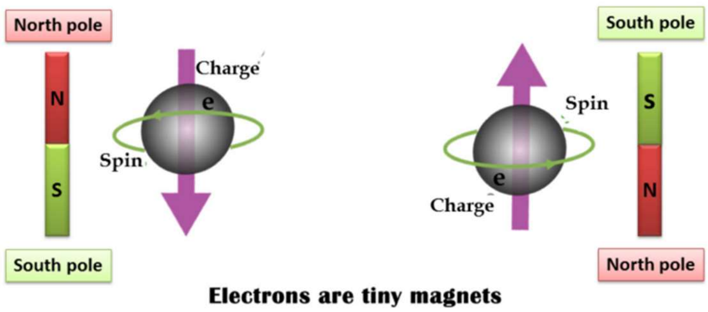

Figure 1. The electron spins can be thought of as tiny magnets, with their direction facing either North-South or South-North. Image taken from [2].

For spintronics to effectively operate and be commercially practicable they rely on multifunctional properties such as ferromagnetism and anti-ferromagnetism [6]. In certain alignments and conditions of these, an effect called giant magnetoresistance effect (GMR) is generated that allows the manipulation of the electrical conductivity inside the structure, and this will be discussed below. The GMR effect is the underlying principle in spintronic devices and is what enabled spintronic research to flourish [3].

3. Giant Magnetoresistance Effect

The giant magnetoresistance effect (GMR) is the change of electrical resistance in a system composed of alternating ferromagnetic and non-magnetic metallic layers. It was first detected by Peter Grünberg and Albert Fert in 1988 and which they received the Nobel Prize in 2007 [7]. Depending on the spin orientation of the electrons with respect to the magnetic orientation within the ferromagnets, the electrical conductivity (resistance) of the structure is altered [8]. Figure 3 is an illustration of the GMR effect.

When the direction of the electron spin is antiparallel with the direction of magnetization of the ferromagnet, the electron scattering is less, thus the resistance inside the ferromagnet is low, and this is indicated by the straight lines on Figure 3. On the contrary, the regions of greater electron scattering, and higher resistance are indicated by the zig-zag lines.

Observing this, it was concluded that when the electron spin is oriented oppositely to the parallel magnetization alignment of the two ferromagnets, it resulted to low resistance in the structure, while high resistance was observed in the antiparallel magnetization alignment of the ferromagnets [10].

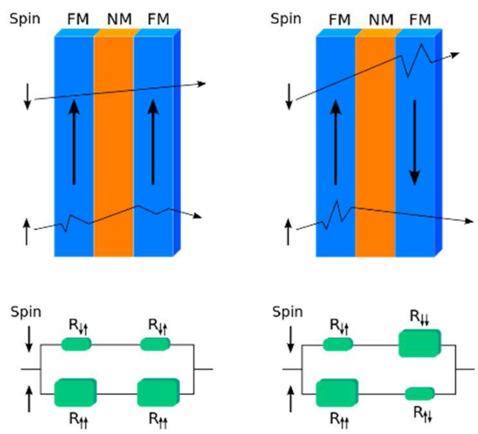

Figure 2. The GMR effect. The two possible alignments of the ferromagnets (FM); parallel and anti-parallel are shown. NM stands for the non-magnetic layer. The electrons having spin up or down scatter differently inside the ferromagnets, modifying the resistance of the structure. Image taken from [9].

After the discovery of GMR, it was quickly recognized that the effect could significantly enhance the read signal and the memory capacitance of Hard disk drives which were previously relied upon the weaker anisotropic magnetoresistance (AMR) [10]. IBM was in fact the first company which produced the first GMR HDDs in 1997 thanks to the invention of the spin valve-sensor [11].

4. Spin-Valve Sensor

The spin-valve sensor paves the way for numerous technological devices, and made huge data centers to store vast amount of data a reality. It contributes greatly to the information-based world that we live in today. IBM researcher Stuart Parkin and his team were the ones that created the spin-valve sensor that is now used in many magnetic sensors and read heads in HDD's. This section discusses the use of the spin-valve sensor inside Hard disk drives [11].

A spin valve sensor is a device that utilizes the effect of GMR. It consists of many layers as shown in Figure 4a. There exists a freely magnetized ferromagnetic layer (FM) at one end, a non-magnetic layer (NM) at the middle, followed by another ferromagnet but this time the direction of magnetization is fixed in this layer, and finally an antiferromagnet at the other end. When a ferromagnet is in close range with an antiferromagnet, an exchange bias effect is generated. This effect aligns the magnetic moments inside the ferromagnet, increasing total magnetization and shifting the magnetic hysteresis loop [12]. This improves the performance of the spin valve sensor and the stability of the magnetic data stored on the disk.

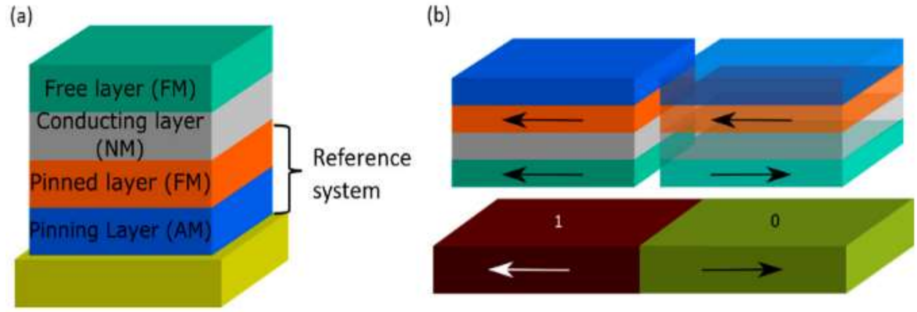

Figure 3. (a) Schematic of GMR spin-valve sensor configuration; (b) The GMR spin valve-sensor moving across a magnetically coated surface between 2 magnetic moments (bits) in opposite directions. The magnetization of the free ferromagnetic layer changes direction. Image taken from [12].

On magnetic disks such as hard disks, the direction of the magnetic field on the coated surface, which faces either North-South or South-North, are interpreted as bits and are assigned as 0 or 1. When the spin-valve sensor moves over the magnetic coated surface, the direction of magnetization on the free ferromagnetic layer obtains the same direction as the coated surface as shown in Figure 4b. This change in magnetic orientation of the free layer with respect to the orientation of magnetization on the fixed layer results to changes in resistance in the structure according to the GMR effect. This change in resistivity, consequently alters the electric current, which is detected and decoded to reveal the data that is stored on the disk [13].

After the discovery of Parkin, every single hard disk drive features a read head as discussed above to store data. Although today, the read heads do not utilize the GMR effect anymore, but instead they use the giant tunneling magnetoresistance effect (or in short tunneling magnetoresistance-TMR), this new effect enhanced their performance [11]. While different physics apply, the effect is still considered spintronic, and will be discussed in the section below.

5. Tunneling Magnetoresistance

TMR effect replaced the GMR effect in the Hard disk drives because it enables a greater value of magnetoresistance to be attained. In contrast to the GMR effect that uses a non-magnetic layer between the two ferromagnets, the TMR effect uses an insulator between the two ferromagnets in a magnetic tunnel junction (MTJ) instead, as shown in Figure 5 [14]. As seen earlier, when a magnetic field acts upon a ferromagnet with a free magnetic layer, its direction of magnetization re-orientates with respect to the applied magnetic field. An antiparallel magnetization orientation of the two ferromagnets results in a smaller number of electrons tunneling through, and this represents a higher resistance in the system. A low resistance is achieved by the parallel magnetization orientation of the two ferromagnets since more electrons tunnel through the insulator [10].

As the name suggests, when this insulator is thin enough, the electrons can tunnel from one ferromagnet to the other. Thus, TMR relies on the phenomenon called quantum mechanical tunneling of electrons. The electrons do not scatter as is the case for GMR, but instead they tunnel through the insulator, all having the same spin direction; either all spin-up or spin-down. The insulator plays an important role in selecting and allowing the same spin electrons. It was found that MgO (magnesium oxide) insulator enables almost 100 percent of electrons with a single spin direction to pass. This implies that the signal of TMR is a lot larger than that of GMR, and indeed it is about 100 times greater [11]. From 2006 until now, the majority of Hard disk drives utilize the TMR effect and use MgO as their tunneling barrier [11].

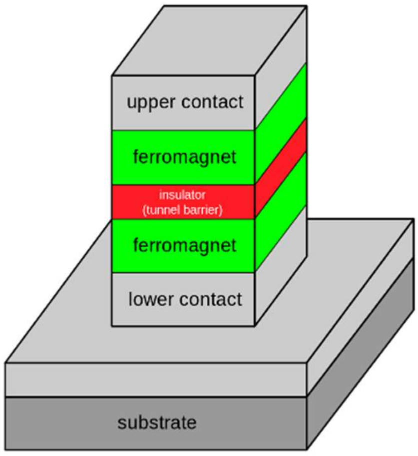

Figure 4. Schematic of a magnetic tunnel junction (MTJ). For TMR to take place the insulator must be a few nanometers thin. Image taken from [14].

6. Magnetic Random Access Memory and Spin Transfer Torque

The TMR effect is also used in magnetic random-access memory (MRAM). MRAM was first developed in 1984 by Arthur V. Pohm and James M. Daughton, while working for Honeywell. Although it has been around since then, its use for just specific tasks and manufacturing challenges slowed down its adoption to technological devices. MRAM however, promises many advantages over traditional RAM. It is non-volatile, meaning that information can still be stored when power is off, it can provide unlimited endurance as it can be written infinitely many times, and can read/write faster with lower power consumption. These make MRAM a strong candidate for becoming the 'universal memory', that is most desired by scientists [15].

Initially, the first TMR-based MRAMs had a cross point architecture and information was written by "word" and "bit" lines, as shown in Figure 6. This structure proved to be expensive in terms of power consumption to switch the magnetization on the free layer. However, in 1996 another IBM researcher called John Slonczewski invented a method that required no magnetic field to flip the magnetic moments inside the free ferromagnet [16]. This method is called spin transfer torque (STT) and utilizes the spin of an incoming electron to transfer torque to other magnetic moments inside a material, hence changing its direction of magnetization. This improved type of MRAM is now known as STT-MRAM [16].

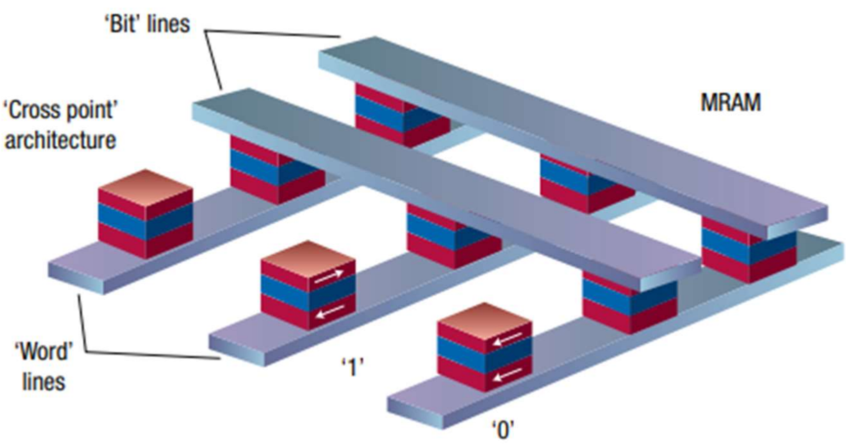

Figure 5. The cross-point architecture of the older MRAM. Information was written on 'word' and 'bit' lines. This architecture proved to be expensive when trying to switch the magnetic moments of the free layer. Image taken from [15].

STT-MRAM uses a magnetic tunnel junction (MTJ) structure with an insulating layer sandwiched by two

ferromagnetic layers. Again, one ferromagnet is freely magnetized, while the magnetization of the other remains fixed. At the fixed layer, a transistor is used for the 'write' purposes, while at the free layer a transistor is used for 'read' purposes [17]. For the writing principle, when current is applied to the structure, firstly it passes through the fixed layer. There the electrons are spin polarized since the electron spin acquires the same direction as the magnetization of the fixed ferromagnet. The electrons are said to be spin polarized, and this spin current continues its journey to the next ferromagnet which is freely magnetized. There, the electrons transfer their torque to the magnetic moments of the free ferromagnet, changing its direction of magnetization. This process is shown by Figure 7. As seen before the resistance inside a magnetic tunneling junction change according to the direction of magnetization of the fixed ferromagnet with respect to the free ferromagnet. A parallel alignment of the two ferromagnets can be assigned the value '0', while the antiparallel alignment can be assigned the value '1' in terms of binary [15]. This is how information is read and written in an STT-MRAM.
STT greatly improved MRAM technology, and currently STT-MRAM scores high in the memory hierarchy due to its higher memory density, speed, endurance, thermal stability and also due to the fact that read, write and store operations can be done simultaneously [18].

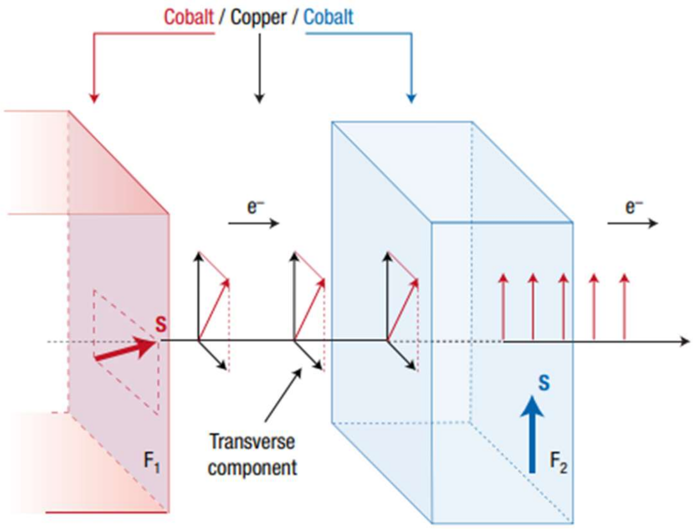

Figure 6. Schematic of how spin transfer torque (STT) operates for writing. The electrons acquire spin polarization when they pass through the first ferromagnet (F1) and later transfer their torque to the magnetic moments of the second free ferromagnet (F2), altering its magnetization and hence the resistance in the structure. Image taken from [15].

7. Future Spintronics

Scientists and researchers across many universities and huge technology corporations such as Samsung, IBM, Intel, Everspin, and more, constantly work on the improvement and development of spintronic devices that will enhance current technology. The last decades, many promising research advances have been made that is worth mentioning in this section. IBM researcher Stuart Parkin, having already contributed so much to the field with his invention of the spin valve, he now works on improving another technology called racetrack memory that can be the future of data storage. He and his co-workers unveiled new characteristics of the physics behind racetrack memory that can allow massive amounts of information to be accessed in less than a billionth of a second. In addition to its remarkable speed, this technology can be inexpensive as well, and can be fitted into handheld devices, and is very likely to be the technology that replaces hard disk drives [19].
As already seen, magnetization switching is very important for changing the electrical conductivity and creating a binary sequence. Another technology in this manner, that is very likely to have great impact in the near-term is magnetization switching by the spin-orbit torques (SOT) induced by the Rashba effect in ferromagnets. Unlike STT that utilizes the angular momentum of the electron, SOT induces spin torque by utilizing the orbital motion of the electron around the atom in a material. STT can only be induced by electric currents only, while SOT can be induced by both electric and thermal currents. SOT through the Rashba effect is very efficient as well, and is very likely to result in room-temperature spintronic applications [20]. Spin current can also be generated through the use of an applied field. This phenomenon is called the spin Hall effect (SHE) and the spin current travels perpendicular to the direction of the applied field. Although SHE is modest in size, scientists reported a giant spin Hall effect in β-tantalum

and this may soon help to overcome problems that current magnetic data storage memory devices face [21].

8. Conclusion

Spintronic technology saw an unprecedented development the past couple decades and experienced great improvements as new methods emerged. Originally a magnetic field was used as a mechanism to switch magnetization but nowadays the most advanced spintronic devices utilize the spin-transfer torque effect to do this. Spintronics have already proved their trustworthiness in the data storage field and that they are a strong candidate to replace traditional electronics. As the field has seen such a great improvement in just 20 years, the next 20 years may as well be even more exciting for spintronics and data storage. Great appreciation needs to be attributed to the ferromagnetic and antiferromagnetic materials also, since their multifunctional properties is what transformed data and allowed the construction of data centers which form the backbone of the information-based world that we live today.

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