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Spintronics - A Dive Into the Future

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ABSTRACT

We already know that electrons have a charge along with a spin, but until recently, these two have been considered separately. The motion of electric charge is considered as the heart of electronic circuits, and the flow of electron spin plays a crucial role in spintronic circuits. Adding the spin degree of freedom provides new capabilities, new effects, and new functionalities. It all started with the discovery of the Giant Magnetoresistance (GMR) in 1988, which opened the road to an effective control of the motion of the electron charges by focusing on their spin through the orientation of magnetization. Today, spintronics has entered into almost every household as the read sensors for the hard drives present in every desktop and most laptops. Magnetic Random Access Memory (MRAM) and Spin Transfer Torque (STT) RAM are replacing Static RAM where ultra-dense memories are not required. Soon these spintronic memories will penetrate the cell phone market because they offer lower power and are non-volatile. The potential held by Spintronics is very promising for new advancements in science and technology in the 21st century. This paper discusses the evolution of spintronics from the initial research of spin-dependent transport in ferromagnetic materials to the discovery of the giant magnetoresistance and to the most recent advances. Today, this field of research is extending considerably, with very encouraging new technologies like the phenomena of spin transfer, molecular spintronics, nanoscale spintronics, and single-electron spintronics.

Keywords : Electron Spin, Spintronics, Magnetoresistance, Spin Transfer

I. INTRODUCTION

In conventional electronics, charges control the electric fields but the spins are generally ignored. Spintronics is the concept of dealing with the spin degree of freedom to control the electrical current in order to enhance the ability of electronic devices. It is concerned with the storage and transfer of data by the means of electron spin in addition to electron charge as in conventional electronics [1].

Semiconductor and ferromagnetic materials are vital for today's electronics technologies. Semiconductor spintronics merges semiconductor microelectronics with spin-dependent effects that arise due to the association between the spin of a charge carrier and the magnetic properties of the materials. Ferromagnetic metals depict a magnetization hysteresis loop in which the motion of a large number of electron spins plays a role. Non-volatile memory devices, such as hard disk drives have been developed by the means of this hysteresis loop. Recently, much attention is being given on the development of Magnetic Random Access Memory (MRAM), which is said to reduce the power consumption because no current is required to maintain it, unlike Dynamic Random Access Memory (DRAM). The MRAM is based on the tunnelling magnetoresistance (TMR) effect arising from the resistance on the spin orientations between two ferromagnetic electrodes [2]. These commercial products may get revamped into standalone memories to replace other random access memories or embedded in Complementary Metal Oxide Semiconductor (CMOS) logic.

Spintronics has appealing potential that may improve sensors and magnetic memories in electronic devices. Some of the spintronics technologies include three-terminal devices based on different characteristics of spin-transfer torques, spin-torque nano-oscillators, and electric fields controlled devices. Even the future holds Spintronics-based applications in different fields like bio-inspired computing, energy harvesting, and quantum technologies [3].

Before we move into the future of Spintronics, we will cover the history of Spintronics.

II. HISTORY OF SPINTRONICS

Spintronics uses the spin degree of freedom of electron charges. The idea of utilising the spin-degree of freedom to control the flow of electrical current dates back to the 1960s in an early research carried out in Reona Esaki's group at IBM demonstrating that an antiferromagnetic bar of EuSe sandwiched between metal electrodes exhibits a large magnetoresistance [4]. Subsequent studies of magnetic multilayers led to the discovery of giant magnetoresistance (GMR) in 1988 by Albert Fert in France and Peter Gruenberg in Germany. This effect was used to develop magnetic sensors to improve the areal density of hard disk drives. The usage of semiconductors for spintronics can be traced back in 1990 when Datta and Das propsed a spin field-effect transistor [Datta, Suprio, and Das Biswajit (1990)].

A. Giant Magnetoresistance

GMR and spintronics travel parallel to each other. The spin dependence of the conduction can be acknowledged from a typical band structure of a ferromagnetic metal shown in Fig.1. The spin of electrons exists in two states – Spin up and Spin down. The splitting between the energies of the "majority spin"(spin up) and the "minority spin"(spin down) directions asserts that the electrons at the Fermi level, carrying the electrical current, are in different states for opposite spin directions and display different conduction properties.

A magnetic multilayer is a film composed of alternate ferromagnetic and nonmagnetic layers, like Fe and Cr. The resistance of such a multilayer is at the lowest when the magnetic moments of ferromagnetic layers are parallel, and highest when they are antiparallel. As the relative difference between these resistances can be as high as 200%, this effect has been termed as Giant Magnetoresistance (GMR) [5]. Patterned multilayers for GMR in a non-conventional configuration where the current hits perpendicular to the layers or magnetic nano-contacts presenting a ballistic version of GMR is known as BMR (Ballistic Magnetoresistance).

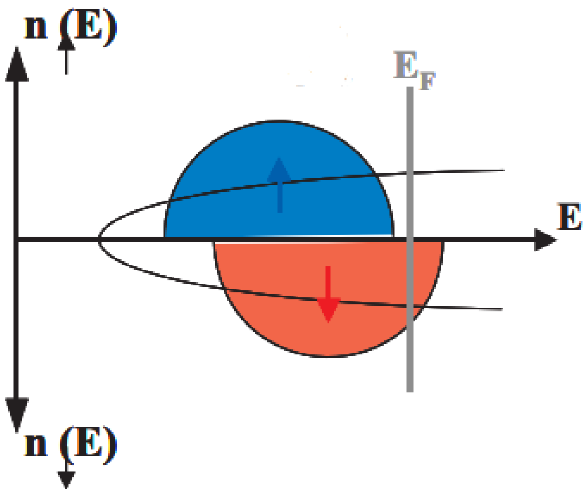

Figure 1: Schematic band structure of a ferromagnetic metal illustrating the energy band spin-splitting.

The basic structure of GMR (Fig. 2) is made up of a layer of non - magnetic metal between two magnetic layers. The condition required for GMR is a much better flow of electrons of one of the spin directions, through a ferromagnetic layer; the majority spin direction for example. When the magnetic moments of all the layers are parallel, half of the electrons are majority spin electrons in all the magnetic layers, and the short circuit effect by this high conduction channel causes a low resistance. In the antiparallel configuration, each electron is alternately a majority (spin up) and a minority spin (spin down) electron, the short circuit effect does not exist and the resistance is much higher.

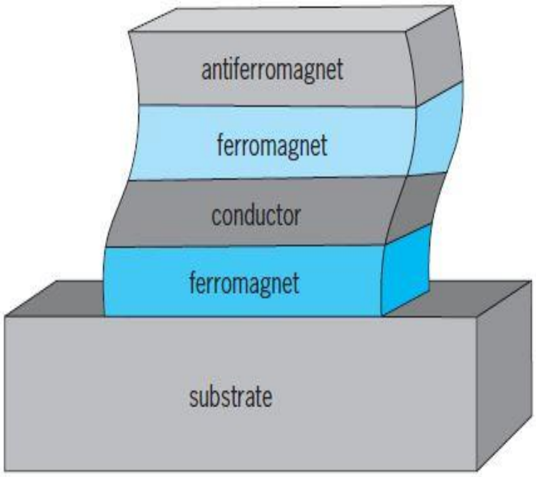

Figure 2: Basic structure of GMR

The magnetic configuration can be switched between parallel and antiparallel configuration by a field of only a few Oersted so that a large difference in resistance can be achieved by a very small field.

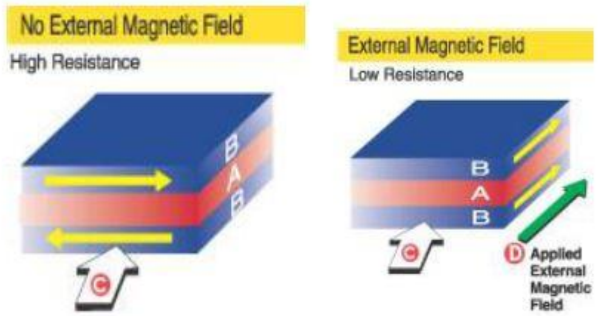

Figure 3: Applying magnetic field lowers the resistance

Figure 3 shows how applying an external magnetic field in a GMR lowers the resistance. Layer (A) is a conductive, nonmagnetic interlayer. Magnetic moments in alloy (B) layers are in opposite directions due to anti-ferromagnetic coupling. Therefore, resistance to current (C) is high. When an external magnetic field (D) is applied, it aligns the magnetic moments in alloy (B) layers and thus overcomes antiferromagnetic coupling. Therefore, the resistance to the current (C) is decreased [6].

B. Magnetic Tunnel Junctions (MTJ) and Tunnelling Magnetoresistance (TMR)

An important phase in the development of spintronics is the research on the Tunnelling Magnetoresistance (TMR) of the Magnetic Tunnel Junctions (MTJ). The basic structure of MTJ (Fig. 4) has two ferromagnetic layers (electrodes) separated by a very thin insulating layer, commonly aluminium oxide. The electrons can tunnel through the insulating layer and, because the probability of tunnelling from a ferromagnetic electrode depends on the spin direction, the resistance of the MTJ is different for the parallel and antiparallel directions of the magnetic moments of the electrodes [7].

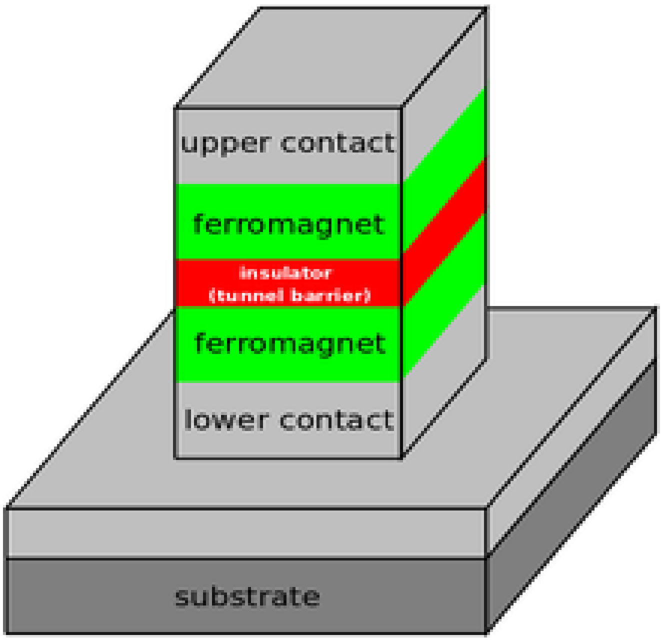

Figure 4: Basic structure of MTJ

Initial viewing of TMR effects at low temperature was reported in 1975, but they were not easily reproducible and actually could not be reproduced until 1995 that large (˜ 20%) and reproducible effects were obtained. The relative change of resistance (TMR) can extend up to 70% at room temperature with the electrodes of conventional ferromagnetic alloys. The MTJ is at the basis of a new concept of magnetic memory called MRAM (Magnetoresistive Random Access Memory) which will be discussed in the later section of this paper.

C. Spintronics with Semiconductors

The inception of semiconductors for spintronics took place with the theory of electric dipole spin resonance proposed by Rashba in 1960 and a spin field-effect-transistor put forward by Datta and Das in 1990 [8]. Semiconductor Spintronics is very captivating as it merges the capability of semiconductors (control of current by gate, coupling with optics) with the capability of the magnetic materials (control of current by spin manipulation, non-volatility) [9].

Spintronics with semiconductors is interesting because it can combine detection, storage, logic, and communication capabilities on a single chip to produce a multifunctional device replacing several components. It can enable a better integration between MTJ and silicon-based electronics than in the present prototypes of MRAM. The optical properties of the semiconductors are also able to convert magnetic information into an optical signal. Finally, because the manipulation of spins shows some advantages in terms of speed and required power over the manipulation of charge in conventional electronics, some concepts of device exploiting these advantages have been already proposed.

Semiconductors for spintronics have an interesting property of long electron spin lifetime. Fine time-resolved magneto-optical experiments performed at the University of Santa Barbara have revealed that spin lifetimes can exceed 100 ns for electrons in bulk semiconductors at low temperatures [10]. In most of these experiments, the spin polarization was created by optical excitation. However, for practical applications, it is highly recommended that the detection and injection of spin currents should be electrical. Some nonmagnetic semiconductors also have a definite benefit on metals in terms of spin-coherence time and spin polarization propagation for long distances.

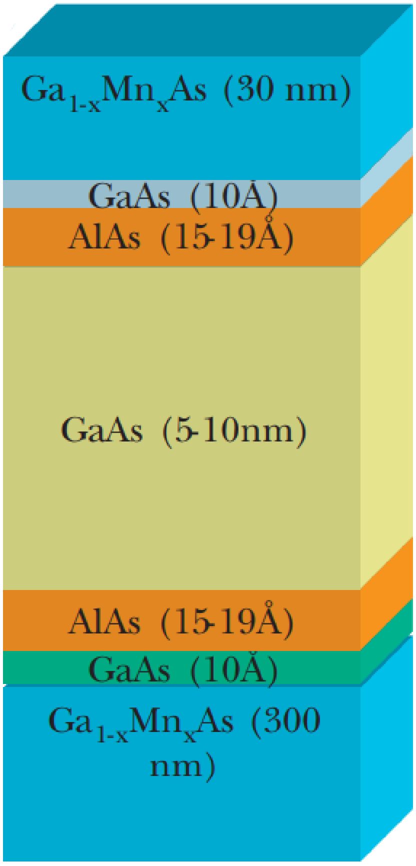

Figure 5: Spintronics with semiconductors structure composed of a GaAs layer separated from the GaMnAs source and drain by tunnel barriers of AlAs

III. RECENT ADVANCEMENTS IN SPINTRONICS

The emerging field of Spintronics has brought game-changing opportunities to the digital world. Nanoscale Spintronics sensors improve the areal density of hard disk drives, through MRAMs (Magnetoresistive Random Access Memory) which are believed to replace the embedded flash. Also, some devices utilize spin current and the resulting torque to produce oscillators and to transfer information without the usage of current. Spintronics devices promise to solve major problems in electronic computers which utilise huge amounts of electricity and generate heat that further requires even more energy for cooling. In strike contrast to this, spintronic devices produce less heat and use relatively less amounts of electricity.

Now, we will look at the advancements more in depth.

A. Magnetoresistive Random Access Memory (MRAM)

MRAM and spin-transfer torque MRAM (STT-MRAM) are non-volatile memories with very high scalability and endurance. This means the information is not lost when the system is switched off. The present STT-MRAM technology uses an array of MTJs with an axis of magnetization positioned out of the layers' plane. These MTJs use interface perpendicular anisotropy, along with the large TMR of the system, for reading the state of magnetization. The magnetization is changed by the spin-transfer torque exerted by a spin-polarized current, offering an effective way of rewriting the memory. The binary information "0" and "1" is recorded on the two opposite directions of the magnetization of Magnetic Tunnel Junctions (MTJ), which are further connected to the crossing points of two perpendicular arrays of parallel conducting lines. For writing, current pulses are transmitted through one line of each array, and only at the intersection of these lines, the resulting magnetic field is high enough to align the magnetization of the free layer. For reading, the resistance between the two lines joining the addressed cell is calculated [11].

The MRAMs are expected to unite the short access time of the semiconductor-based RAMs and the non-volatile nature of the magnetic memories. In the first MRAMs, the memory cells were MTJs with an alumina barrier. The magnetic fields generated by "word" and "bit" lines are used to switch their magnetic configuration, see Fig. 6. The MRAM, based on MgO tunnel junctions and switching by spin transfer, is expected to have a much stronger impact on the computer technology.

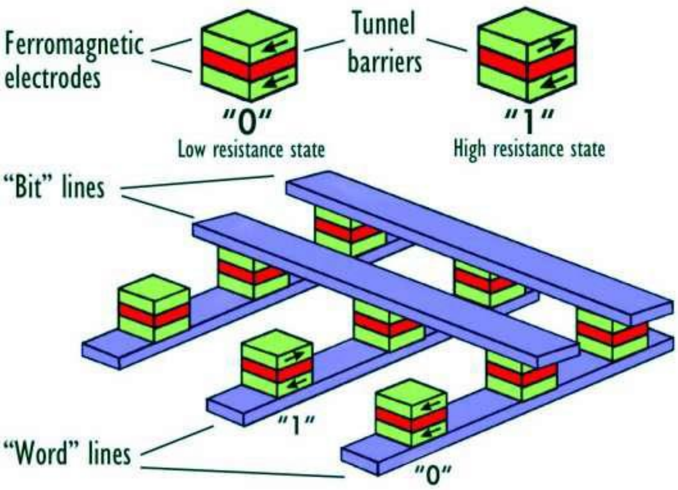

Figure 6: The basic "cross point" architecture of MRAM

B. Modern Hard Disk Drives

Two types of Spintronics sensors have replaced traditional Anisotropic Magnetoresistance (AMR) sensors. These sensors include Giant Magnetoresistance (GMR) sensors used in hard disk drives from 1998 to 2004 and Tunnel Magnetoresistance (TMR) sensors that are being used since 2004.

These sensors are part of the technology development that enhanced the storage density of hard disk drives by several orders of magnitude, is the pioneer of today's information age in the form of data centres set up by the cloud computing industry.

C. Three Terminal Magnetic Memory Devices

Recent developments in Physics have raised the prospect of three-terminal spintronic memory devices. These devices have an edge over the standard two-terminal devices such as MRAM. Dividing the read and write functions in MRAM potentially overcomes several future roadblocks in the development of MRAM. There are two writing schemes: The first one is based on spin currents caused by an electrical current passing through a heavy metal adjoining the free layer of the MTJ. This current causes a spin current both in the heavy metal and at the interface; this spin current then applies a torque called the spin-orbit torque, on the magnetization. In this scheme, the write current does not pass through the MTJ, thus separating the write and read functions. The second scheme uses current-induced domain wall motion to shifts a domain wall in the free layer of the MTJ from one side of the fixed layer to the other. In this scheme, the current moves through the free layer, but not the tunnel barrier, thus separating the read and write functions [12].

D. Spin-Torque and Spin-Hall Nano-Oscillators

Spin-torque nano-oscillators (STNO) and spin-Hall nano-oscillators (SHNO) are in a group of concentrated and ultra-broadband microwave signal generators that are based on magnetic resonances in single or coupled magnetic films where magnetic torques are used to excite the resonances and subsequently tune them as well. These torques can be in two forms, spin-transfer torques due to spin-polarized currents (STNOs) or spin Hall torques because of pure spin currents (SHNOs). These devices are auto-oscillators and do not require any active feedback circuitry with a positive gain for their operation [13]. The auto oscillatory state causes phase-amplitude coupling, which governs a wide range of properties, including frequency tunability, injection locking, modulation, mutual synchronization, but also causes remarkable phase noise. These two oscillators can operate at any frequency supported by a magnetic mode, this results in a potential frequency range from below 100 MHz for magnetic vortex gyration modes to beyond 1 THz for exchange dominated modes [14]. Since STNOs and SHNOs can also act as tunable detectors at this frequency range, hence there is a significant potential for novel devices and applications as well.

E. Spintronic Nanodevices for Bioinspired Computing

Bioinspired computing devices promise low-power, high-performance computing but will likely depend on devices beyond CMOS. It relies on ultra-high density networks manufactured out of complex processing units linked by tunable connections. There are several methods in which spin-torque-driven MTJs, with their CMOS compatibility and tunable functionalities, are very well adapted for this purpose. Some groups have recently presented a variety of bioinspired architectures that include one or several types of spin-torque nanodevices.

F. Skyrmion-Electronics

The concept of skyrmions comes from high energy physics. In magnetic systems, skyrmions are termed as magnetic textures that can be viewed as topological objects. Magnetic skyrmions are believed to possess topologically protected stability and nanoscale size, and they require a very low driving current density; hence they are considered as possible building blocks for future spintronic devices and integrated circuits. Recent theory suggests that they have properties that might make them beneficial objects to store and manipulate information. Many of these ideas are similar to the ones that were developed decades ago for bubble memory or, more recently, racetrack memory. There are several possible benefits for skyrmion devices as compared to other related devices. Moreover, the latest experiments on individual nanosize skyrmions, including their control, formation, movement, detection, and manipulation at room temperature, underline their capability for future electronic applications [15].

IV.FUTURE OF SPINTRONICS

The future of Spintronics is quite uncertain but, surely, that Spintronics will continue to have an increasing impact on the Electronics world. The importance of magnetic sensors is likely to remain important while its importance in hard disk drives may degrade due to the mass storage in the cloud. In the future, Spintronics can play a vital role in areas such as IoT, high-performance computing (HPC), ultralow-power electronics. Besides, in the next decade, we are likely to see a much greater role played by alternative forms of computing. The role that Spintronics plays in those technologies is likely to be strongly impacted by the success of MRAM.

Materials permitting effective charge to spin and spin to charge current conversion or good control of magnetic properties by voltage can play major roles. Along with this theory, the usage of oxide materials in spintronic devices may become quite important. Oxides share crystallinity with semiconductors and the great control that comes with crystallinity may become beneficial to oxides in future devices. This is one of the many topics that are likely to be addressed in the coming years [16].

V. CONCLUSION

In less than two decades, we have seen spintronics considerably increasing the capacity of our hard discs, extending the hard disc technology to mobile appliances like cameras and portable multimedia players, entering the automotive industry, biomedical technology, and the RAM of our computers with TMR and spin transfer. This technology promises more compact and faster electronic gadgets. Today's research on the spin-transfer phenomena, on ferromagnetic materials, on spintronics with semiconductors and molecular spintronics, open fascinating new fields and are also very promising of multiple applications. Spintronics is still in the research phase and we hope that this new technology should take an important place in the science and technology of the century.

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