Spintronics - A New Hope for the Digital World

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Abstract- In our electronic world, since the discovery of electron by J J Thomson in 1897, scientists have been working strenuously to build the Digital World that we enjoy today. To satisfy a common man's need, researchers have been scratching the very basis of electronics – 'Electron'.

All that we are using today is the flow of a bundle of electrons to determine the electronic outcome instead of the basic property of electron, which is to 'Spin'. They started exploiting this property leading to the rise of a new technology – Spintronics.

Spintronics came into lime light in 1988 when French and German physicists Albert Fert et al (in Paris) and Peter Grunberg et al (in Jullich) independently discovered the Giant Magneto Resistance (GMR). This discovery is considered to be the birth of spintronics. The two physicists have earned a number of prestigious prizes and awards for their discovery and contribution in the field of spintronics, including the 2007 Noble Prize in Physics.

Spintronics is based on the spin of electrons existing in one of the two states, namely spin up and spin down, with spin either positive half or negative half. In other words, an electron can rotate either clockwise or anti-clockwise around its own axis with constant frequency. The two possible spin states naturally represent '0' & '1' in logical operations.

All spintronic devices act according to the simple scheme: (1) information is stored (written) into spins as a particular spin orientation (up, down); (2) the spins, being attached to mobile electrons, carry information along a wire and; (3) the information is read at terminal.

The two important effects based on spintronics are the Giant Magneto Resistance (GMR) Effect and Tunnel Magneto Resistance (TMR) Effect, where GMR is the ferromagnetic alloy sandwiched around an ultra-thin non-magnetic middle layer. In this, the resistance changes depending on whether the moment of magnetic layer are parallel (low resistance) or anti-parallel (high resistance) while the TMR is a magneto resistive effect that occurs in magnetic tunnel junction.

The various spintronic devices based on the above two effects are GMR sensor, spin valve, MRAM (Magneto resistive RAM), disks read / write heads of a disk drive, magnetic field sensors and one of the most promising aspects is quantum computers, where electron spin would represent a bit – called qubit – of information.

These devices find a variety of applications in the field of automobile, telecommunication and in various electronic gadgets. This technology promises cheaper, compact and faster electronic gadgets. There are certain challenges in this technology concerning the detection of spin of electron, controlling the spin of electron and transferring the spin of electron under which research is still in progress.

This technology has great potential to spin the global village into a technological revolution.

Index Terms- Spintronics, GMR , TMR, MRAM

I. Introduction

Spintronics (a neologism meaning "spin transport electronics"), also known as magneto electronics, is an emerging technology that exploits both the intrinsic spin of the electron and its associated magnetic moment , in addition to its fundamental electronic charge, in solid-state devices .[Patel MV , Parmar MN , Chaudhari JM and Patel CD (2011)]

Spintronics is a new branch of electronics in which electron spin, in addition to charge, is manipulated to yield a desired electronic outcome. All spintronic devices act according to the simple scheme: (1) information is stored (written) into spins as a particular spin orientation (up or down), (2) the spins, being attached to mobile electrons, carry the information along a wire, and (3) the information is read at a terminal. Spin orientation of conduction electrons survives for a relatively long time (nanoseconds, compared to tens of femto seconds during which electron momentum and energy decay), which makes spintronic devices particularly attractive for memory storage and magnetic sensors applications, and, potentially for quantum computing where electron spin would represent a bit (called qubit) of information.

II. HISTORY OF SPINTRONICS

Spintronics came into lime light in 1988 when French and German physicists Albert Fert et al (in Paris) and Peter Grunberg et al(in Julich) independently discovered a much powerful effect called "Giant Magneto Resistance" (GMR). The origins of spintronics can be traced back even further to the observation of spin-polarized electron injection from a ferromagnetic metal to a normal metal by Johnson and Silsbee (1985),ferromagnetic/superconductor tunneling experiments pioneered by Meservey and Tedrow,and initial experiments on magnetic tunnel junctions by Julliere in the 1970s[Julliere M (1970)].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[Datta, Suprio and Das Biswajit (1990)].

III. THEORY

Spintronics is based on the spin of the electron exists in one of the two states, namely spin up and spin down, with spins either positive half or negative half. In other words, an electron can rotate Either in clockwise or anticlockwise around its own axis with constant frequency.

An approximate understanding of the nature of spin can be gleaned by analogy with the orbit of planets in the solar system. In this analogy, electrons orbit a nucleus in a fashion similar to the Earth's orbit around the Sun. Just as the Earth rotates about It's axis during the orbit, electrons have a quality of rotation called 'spin.

The total magnetic moment of an electron is equal to the sum of its spin moment (on account of its spin about its own axis) and the orbital (on account of its orbit around nucleus of an atom).

$$\vec{m}_{\text{electron}} = \vec{m}_{\text{spin}} + \vec{m}_{\text{orbit}}$$

where:

$$\vec{m}_{\text{spin}} = -\frac{q}{m_e}\vec{S}$$

$$\vec{m}_{\text{orbit}} = -\frac{q}{2m_e}\vec{L}$$

It is found that the spin moment given by $m_{\text{spin}} = -\frac{q}{m_e}S$ is twice as strong as the orbital moment.

The spin moment S is quantized and can be obtained from:

$$|\vec{S}| = \sqrt{s(s+1)}\hbar$$

Where $s = \frac{1}{2}$ is the spin angular momentum quantum number, so the magnitude of the spin moment is always:

$$|\vec{S}| = \frac{\sqrt{3}}{2}\hbar$$

The orientation of the vector magnitude S is also restricted. Specifically, it's projection onto a given axis is given by the spin projection quantum numbers.

$$S_z = m_s\hbar$$

Where

$$m_s = \pm\frac{1}{2}$$

$$\Rightarrow m_{\text{spin,z}} = -2m_s\mu_B$$

In a normal metal spin up and spin down are equal in number so they cancel the effect of one another .As spin effect is neutralized so there is no surplus moment piling up.

For that, a ferromagnetic material like iron, nickel or cobalt is needed.

These have tiny regions called 'domains' in which an excess of electrons have spins with axes pointing either up or down –at least, until heat destroys the magnetism, above the metal's curie temperatures. The many domains are ordinarily randomly scattered and evenly divided between majority up and majority down. But an externally applied magnetic field will move the walls between the domains and line up all the domains in the direction of the field , so, they point is a permanent magnet.

There are two ways for spins to decay:-

- Impurities can induce spin orbit coupling.
- A spin-orbit interaction can be induced by host lattice ions.

The second mechanism is important at high temperatures where electrons scatter off phonons, but also at low temperatures, if the impurities are light—meaning they induce small spin-orbit coupling. The second mechanism is somewhat tricky.

One has to realize that in the presence of spin-orbit coupling, spin up and spin down states are no longer good quantum numbers even scalar (spin independent) interactions due to impurities or phonons can cause spins to flip.

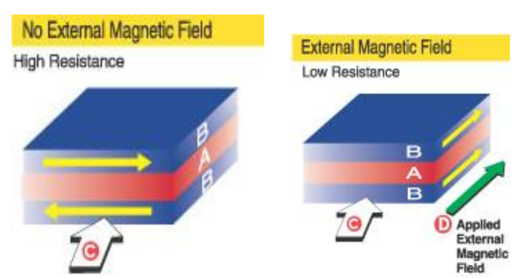
IV. GMR (GIANT MAGNETO RESISTANCE)

"GMR can be considered one of the first real applications of the promising field of nanotechnology."

—Nobel Prize Committee, October 2007

What's Giant in "Giant Magneto resistance"? Although the term "giant" in giant magneto resistance (GMR) seems incongruous for a nanotechnology device, it refers to a large change in resistance (typically 10 to 20%) when the devices are subjected to a magnetic field, compared with a maximum sensitivity of a few percent for other types of magnetic sensors.

GMR structures are ferromagnetic alloys sandwiched around an ultrathin nonmagnetic conducting middle



Layer (A) is a conductive, nonmagnetic interlayer. Magnetic moment in alloy (B) layers face opposite directions due to anti-ferromagnetic coupling. Resistance to current (C) is high. The nonmagnetic conducting layer is often copper. Copper is normally an excellent conductor, but when it is only a few atoms thick, electron scattering causes copper's resistance to increase significantly. This resistance changes depending on the relative orientation of electron spins surrounding the conducting layer

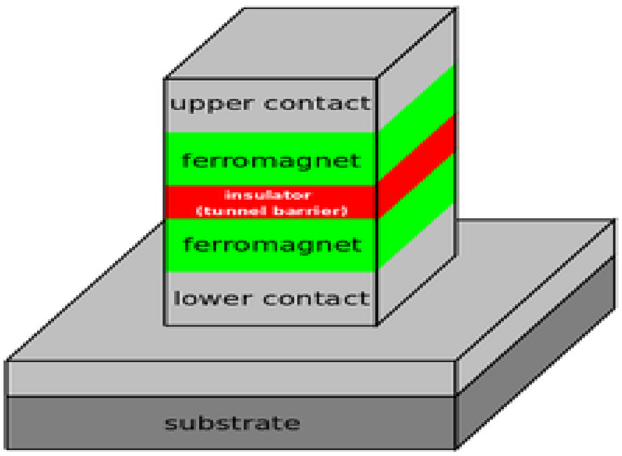
Applying an external magnetic field (D) overcomes anti ferromagnetic coupling, aligning magnetic moments in alloy (B) layers:

Such exposure changes the device resistance so the structure can be used to sense an external field. Practical devices are often made of multiple layers of alternating magnetic and nonmagnetic layers to improve sensitivity.[M Carl Smith and Robert N Schneider (No Date)]

In a GMR spintronic device, the first magnetic layer polarizes the electron spins. The second layer scatters the spins strongly if its moment is not aligned with the polarizer's moment. If the second layer's moment is aligned, it allows the spins to pass. The resistance therefore changes depending on whether the moments of the magnetic layers are parallel (low resistance) or anti -parallel (high resistance).

V. TMR & MTJ

The Tunnel magneto resistance (TMR) is a magneto resistive effect that occurs in magnetic tunnel junctions (MTJs). This is a component consisting of two Ferro magnet separated by a thin insulator. If the insulating layer is thin enough (typically a few nanometers), electrons can tunnel from one ferro magnet into the other. Since this process is forbidden in classical physics, the tunnel magneto resistance is a strictly quantum mechanical phenomenon

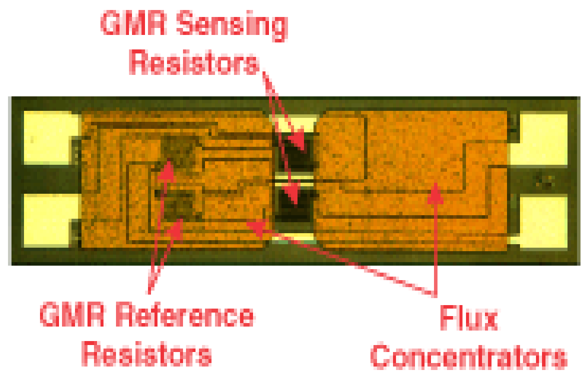


Magnetic tunnel junction (schematic)

Magnetic tunnel junctions are manufactured in thin film technology. [Fert Albert et al (31 aug 2008)]On an industrial scale the film deposition is done by magnetron sputter deposition; on a laboratory scale molecular beam epitaxial, pulsed laser deposition and electron beam physical vapor deposition are also utilized. The junctions are prepared by photolithography.

VI. SPINTRONICS DEVICES AND THEIR APPLICATIONS

Spintronics GMR Sensor: A photomicrograph of a typical GMR magnetic sensor, also known as a magnetometer is shown below:



In a typical sensor, four GMR resistors are configured as a Wheatstone bridge. A bridge configuration provides an easy-to-use voltage output that is proportional to the magnetic field applied but insensitive to any variations in the absolute resistance of the GMR device.

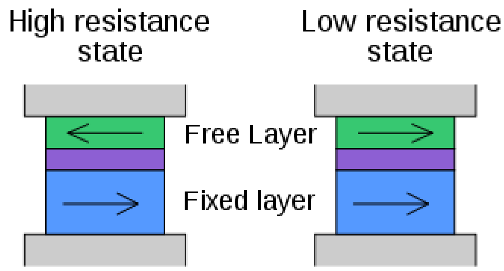
Two of the resistors are sensing resistors; the other two are reference resistors. The reference resistors are covered by a nickel-iron magnetic shield that measures 0.0004 in. thick. In response to an external magnetic field, the exposed sensing resistors decrease in electrical resistance while the reference resistors remain unchanged, causing a voltage at the bridge output.

GMR sensors find a wide range of applications.

- Fast and accurate position and motion sensing of mechanical components in precision engineering and robotics.
- All kinds of automotive sensors for fuel handling system, anti – skid systems, speed control and navigation.
- Position motion sensing in computer video games.
- Key hole surgery and post operative care.

SPIN VALVE: A **spin valve** is a device consisting of two or more conducting magnetic materials that alternates its electrical resistance (from low to high or high to low) depending on the alignment of the magnetic layers, in order to exploit the Giant Magneto resistive effect.

The magnetic layers of the device align "up" or "down" depending on an external magnetic field. Layers are made of two materials with different magnetic coercitivity, due to the different coercivities one layer ("soft" layer) changes polarity at small magnetic fields while the other ("hard" layer) changes polarity at a higher magnetic field. As the magnetic field across the sample is swept, two distinct states can exist, one with the magnetizations of the layers parallel, and one with the magnetizations of the layers anti - parallel. In the figures below, the top layer is soft and the bottom layer is hard.



If an electrons encounter a material with a magnetic field pointing in the opposite direction, they have to flip spins to find an empty energy state in the new material. This flip requires extra energy which causes the device to have a higher resistance than when the magnetic materials are polarized in the same direction.

Spin valves are not only highly sensitive magnetic sensors but these can also be made to act as switches by flipping magnetization in one of the layers parallel or anti parallel as in a convectional transistor memory device.[Wolf SA (2006)]

MAGNETO RESISTIVE RANDOM ACCESS MEMORY: **Magneto resistive Random-Access Memory** is a non-volatile computer memory (NVRAM) technology i.e., the information isn't lost when the system is switch off. Unlike conventional **RAM** chip technologies, in MRAM data is not stored as electric charge or current flows, but by magnetic storage elements. The elements are formed from two ferromagnetic plates, each of which can hold a magnetic field, separated by a thin insulating layer. One of the two plates is a permanent magnet set to a particular polarity, the other's field can be changed to match that of an external field to store memory. This configuration is known as a spin valve and is the simplest structure for a MRAM bit. A memory device is built from a grid of such "cells". [Akerman Johan (2005)]

MRAM has similar performance to SRAM, similar density of DRAM but much lower power consumption than DRAM, and is much faster and suffers no degradation over time in comparison to flash memory. It is this combination of features that some suggest make it the "universal memory", able to replace SRAM, DRAM, EEPROM, and flash. They can survive in high temperature or high level of radiations or interference.

Proposed uses for MRAM include devices such as:

Aerospace and military systems	Digital cameras
Notebooks	Smart cards
Mobile telephones	Cellular base stations
Personal Computers	Battery-Backed SRAM replacement
Media players	Book readers

Motorola has developed a 1st generation 256 kb MRAM based on a single magnetic tunnel junction and a single transistor and which has a read/write cycle of under 50 nanoseconds (Ever spin, Motorola's spin-off, has since developed a 4 Mbit version).

DISK READ / WRITE HEADS: D**isk read/write heads** are the small parts of a disk drive, that move above the disk platter and transform platter's magnetic field into electrical current (read the disk) or vice versa – transform electrical current into magnetic field (write the disk). The heads have gone through a number of changes over the years.

Traditionally the heads themselves are made up similar to the heads in tape recorders—simple devices made out of a tiny C-shaped piece of highly magnetizable material called ferrite wrapped in a fine wire coil. Then the Metal In Gap (MIG) replaced a traditional technology allowing 3.5 inch drives to reach 4GB storage capacities in 1995.

The next head improvement was to optimize the thin film head for writing and to create a separate head for reading. The separate read head uses the magneto resistance (MR) and giant magneto resistance effect which changes the resistance of a material in the presence of magnetic field.
In 2005, the first drives to use tunneling MR (*TMR*) heads were introduced by Seagate allowing 400 GB drives with 3 disk platters.

QUANTUM COMPUTERS : one of most ambitions devices is the spin based quantum based computer in solid state structures using electron spin for this purposes is a obvious idea since fermions with ½ spin is a natural and intrinsic qubit.

The applications of spintronics in quantum computation has focused on using quantum-dot-trapped electron spins in GaAs .Because of the three dimensional confinement and the fact that GaAs conduction band is mainly band in mainly formed from 's' atomic orbital , the trapped electrons have a small spin –orbit coupling and therefore small decoherence rate. In the Qd-Qc model, one electron spin per quantum dot works as a quantum qubit. Two coupled spins on two neighboring dots provide two qubit operations through the inter dot electronics exchange coupling. The external magnetic fields provide means to manipulate single qubits.

VII. FUTURE OF SPINTRONICS

In less than twenty five years, we have seen spintronics increasing considerably the capacity of our hard discs and getting ready to enter the RAM of our computers or the microwave emitters of our cell phones. Spintronics with semiconductors or molecules is very promising too. It can also be mentioned that another perspective, , might 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. Spintronics should take an important place in the technology of our century.

VIII. CONCLUSION

This technology which exploits the spin of electron has great potential to spin this global village into a technological revolution. This technology has already entered our home as we use spintronic device in our desktop, (since the read head of hard drive today use GMR to read information on the disk). This technology promises cheaper, compact and. faster electronic gadgets. Spintronics is still in research phase and we hope that this new technology can be used in labs to look at problems that interest researchers.

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