SC-221 Engineered Materials

SPINTRONICS

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INTRODUCTION

Spintronics is a prominent technology that utilizes the intrinsic spin of the electron and its associated magnetic moment, along with a fundamental electronic charge in devices. It is also known as magneto electronics.

In our conventional electronic devices, electron charge was used to achieve functionalities and semiconductors for logical operation and magnetic materials for storage. But, spintronics functions on the electron spin and resulting magnetic moment to meet improved features, and also magnetic materials are used for processing and storage. These devices are remarkably smaller, more versatile, and more robust than those current circuit elements.

Magneto Resistance is the property of a material to change the value of its electrical resistance on the application of the external magnetic field. This effect was first discovered by William Thomson in 1856. The drawback was that he was unable to lower the electrical resistance of anything by more than 5%. This effect was later termed Anisotropic Magneto Resistance (AMR) to distinguish it from GMR. Spintronics came into light by the invention of Giant Magneto Resistance (GMR) in 1988.

It results from electron spin effects in multilayers of magnetic materials that cause a massive change in electrical resistance. GMR is a magnetoresistance effect observed in thin-film structures formed by alternating ferromagnetic and insulating(non-magnetic) layers. Magnetoresistance is calculated by following equation MR = (RAp-RP)/Rp.

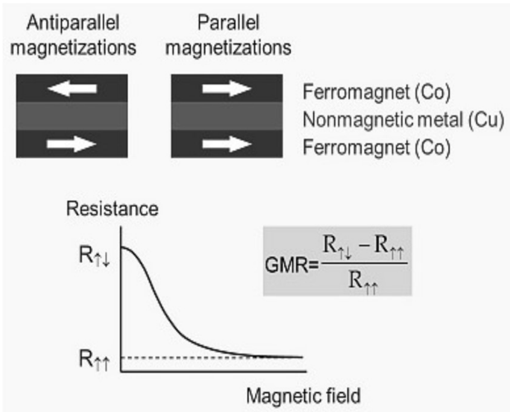
The 2007 Nobel prize in physics was awarded to Albert Fert and Peter Grunberg for the creation of GMR. The effect is observed with a huge difference when adjacent ferromagnetic layers are in a parallel or an antiparallel alignment. The resistance is relatively high for antiparallel alignment and relatively low for parallel alignment. There are active and passive devices of spintronics technology.

Spin valve, GMR (Giant Magneto Resistance), MTJ (Magnetic Tunnel Junction), FTJ (Ferroelectric Tunnel Junction), DW (Domain Wall) are active devices.

GIANT MAGNETO RESISTANCE(GMR)

It was discovered that when the magnetic field is applied to materials such as Fe\Cr and Co\Cu, constructed as ferromagnetic layers are separated by non-magnetic material layers of about 1nm thick, which results in a significant reduction of electrical resistance of the multilayer. This effect was found to be larger than other magnetoresistive effects that had been observed until now. So was called Giant Magneto Resistance (GMR). In Co/Cu and Fe/Cr multilayers, the magnitude of GMR can be higher than 100% at low temperatures.

As shown in the figure, when the magnetic field is applied to multilayer, the magnetic moments of the ferromagnetic layers are aligned parallel dependent on the magnetic field. In the absence of the magnetic field, the magnetic moments of the ferromagnetic layers are antiparallel. The applied magnetic field aligns the magnetic moments and saturates the magnetization of the multilayer, leads to a decrement of the electrical resistance of the multilayer. Earlier resistance of multilayer was



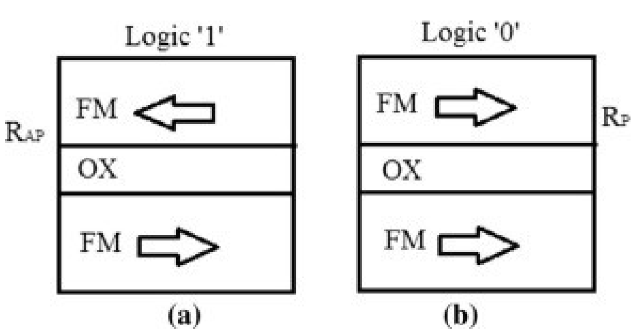
measured with the Current in Plane (CIP). But this suffers from several drawbacks such as shunting, channeling, etc. To deal with these problems started measuring with Current Perpendicular to the Plane (CPP), as electrons cross all magnetic layers. Still, a practical difficulty is that the perpendicular resistance of ultra-thin multilayers is too small to be measured by common techniques. The Microfabrication techniques are used for CPP measurements, Fe/Cr multilayers were etched into micropillars to obtain a relatively large resistance (a few milliohms) from 4.2K to 300K was first shown.

GMR is nowadays used in modern hard drives and magnetic sensors. In 1994, the first magnetic sensor using GMR was released, later IBM produced the first GMR read heads for reading data stored in magnetic hard disks. A spin valve(a type of GMR effect) is also used in Magnetic Random Access Memory (MRAM). In 1997 Honeywell produced the very first GMR based RAM chips. Today GMR based read heads are frequently used in portable devices. There are three types of GMR multilayer, spin valve and granular. In multilayer, two or more magnetic layers are separated by a very thin (about 1 nm) non-magnetic (insulating) layer. Ferrite (iron (III) oxide) is a magnetic layer, and chrome is an insulating layer. In spin-valve GMR, two magnetic layers are separated by a thin (about 3 nm) non-magnetic (insulating) layer. Materials used in spin valves are copper and an alloy of nickel and iron. Spin valve GMR is the most used for hard drives.

Magneto Tunnel Junction (MTJ)

Magneto Tunnel Junction is a tunnel junction used for logic and memory applications. It is a combination of magnetism and electronics, which functions at high read & write speed, non-volatility, infinite endurance, etc. One of the important devices of spintronics is MTJ nano-pillars. An MTJ nano-pillar is similar to the Spin valve consist of two ferromagnets separated by an ultra-thin layer of oxide (insulating layer of around nm). Here the Non-Magnetic layer (Cr or Cu) used in the spin valve is replaced by a very thin barrier layer of oxide Al2O3 or MgO.

Tunnel Magneto Resistance occurring in MTJ is defined as the relative orientation of antiparallel and



parallel resistance. In practice, one of the layers is initially aligned by the magnetic field and known as the reference layer, while other magnetic layers magnetic moment defines the binary state by the relative orientation of both layers. If the alignment of magnetic moments in parallel, then it will read as binary state 0 or 1 else in antiparallel alignment will be interpreted as 1 or 0. It works like when a current or electron is passed through MTJ, resistance for parallel alignment is relatively very low as compare to antiparallel. Recently research founded that TMR ratio was more than 604% at room temperature, and more than 1100% at 4.2K are observed in junctions by using the MgO layer, and this defines MTJ as perfect for sensor design. MTJs are manufactured by thin-film technology. The film deposition is carried out by magnetron sputter deposition, molecular beam epitaxy in industrial and laboratory scale. Pulsed laser deposition and electron beam physical vapor deposition are also utilized for film deposition. Nowadays, MTJ can be improved by various ways in which few are, appropriate selection of material, scalability, energy efficiency, reliability, power consumption, etc.

In the 21st century, GMR based read heads are replaced TMR based read heads. MRAM chips based on TMR devices are now adapted by several companies, such as Freescale, SanDisk, etc. The impact of GMR/TMR technology is rapidly growing and has now become a billion dollars industry. The second-generation techniques currently being developed are Thermal Assisted Switching (TAS) and Spin Torque Transfer (STT). Currently, several companies are working on them. This enhances data reliability, power efficiency, and performance, etc. CMOS circuits and MTJ can be integrated to develop hybrid technologies. NV memory (magnetic) and NV logic have been prepared based on the hybrid combination of CMOS and MTJ.

Magnetic Random Access Memory (MRAM)

When we hit a power button to a computer or laptop, but it takes a sequence of time to boot-up. Perhaps, this thing never happens with TV or radio, because it never had a memory or hard disk to boot-up. But now this boot-up is going to eliminate by the use of new technology, according to IBM. This is at another level from dynamic RAM (DRAM), the dominating type of memory in use. MRAM promises the same read and writes speed of memory. DRAM requires a continuous supply of electricity, which makes it inefficient. IBM Corp. and Infineon Technologies were charging on a task for developing an MRAM since the 1990s. Magnetic RAM, as its name suggests, is going to be focused on the magnetic property or say spin of the electron alongside with electron charge. MRAM utilizes magnetism instead of electric power to store data. MRAM is the key to store more data, access data faster, and comparatively less power consumption. In modern technology, electric charge is used to store data. But the drawback is it requires constant electric power to keep the memory cells to maintain its charge. MRAM has magnetic property as its center, which makes it non-volatile and requires no electrical power. It is believed that the advantages of MRAM are so overwhelming that it will dominate the market.

A memory device is built by a grid of cells. A cell constructed by two ferromagnetic layers, one of them has initial polarity called reference layer, separated by a thin insulating layer. The reference layer is set to a permanent polarity. Remaining one has polarity associated with the external field. A cell can be read by the relative orientation of magnetic moments, describing its electrical resistance. Many remarkable signs of progress had been made in the past decades in MRAM. Many associate technologies have been used to enhance MRAM. One of them is spin-transfer torque.

When a spin-polarized current is passed through the magnetic layer of a TMR or spin valve, the orientation of the magnetic layer can be modified. This effect is termed as spin-transfer torque. Charge carriers have a property of spin intrinsic to the carrier. In standard current or unpolarized current, the spin consists of 50% spin-up and 50% spin-down electrons. By polarizing a current, it includes majority electrons of either spin. Polarized current can be obtained by passing it through a thick magnetic layer. Spin transfer torque random access memory (STT-RAM), which enhances the power efficiency and scalability in comparison to MRAM, which uses magnetic fields to flip the active elements. MRAM devices at low current requirements and reduced costs can be possible with STT. The amount of current required to reorient the magnetization presently is too high for majority commercial applications. The reduction of this current is the basis for research in spintronics. Several companies are exploring for the commercial development of STT-RAM. In June 2009, Hitachi, along with Tohoku University, demonstrated a 32-MB STT-RAM.

One recent discovery, a novel method for switching the magnetization in the free layer, is already in use by IBM and Freescale. The change is in this approach, the free layer is replaced by a artificial ferromagnetic layers separated by a thin layer of ruthenium.

Till, now many memory technologies have evolved, some of them and their properties are shown below.

	SRAM	eDRAM	DRAM	eFLASH(NOR)	FLASH(NAND)	FeRAM	PCM	STT-RAM	RRAM
Endurance (cycles)	Unlimited	Unlimited	Unlimited	10^5	10^5	10^{14}	10^9	Unlimited	10^9
Read/Write Access time(ns)	<1	1-2	30	$10/10^3$	$100/10^6$	30	10/100	2-30	1-100
Density	Low(6 transistors)	Medium	Medium	Medium	High(multiple bits per cell)	Low(limited Scalability)	High(Multiple bits per Cell)	Medium	High(Multiple bits per cell)
Write power	medium	medium	medium	high	high	medium	medium	medium	medium
Standby power	high	medium	medium	low	low	low	low	low	low
Other	Volatile	Volatile. Refresh Power and time needed	Volatile. Refresh Power and time needed	High voltage required	High voltage required	Destructive readout	Operating T<125° C	Low read signal	Complex Mechanism

Here:-SRAM=Static RAM, eDRAM=Embedded dynamic RAM, FeRAM=Ferroelectric RAM, PCM=Phase change memory, STT-RAM=Spin Transfer torque RAM, RRAM=Resistive RAM.

Another key development is spin momentum transfer (SMT) that can be used for further scaling of MRAM. This is not the end; there is furthermore to surprise. After tackling all the difficulties faced to utilize spintronics in commerce, it will be the future of storage and memory. This can be the key to quantum computers and communication, which can lead to a new perspective on information technology.

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