SPINTRONICS:- The New Era of Nano Technology

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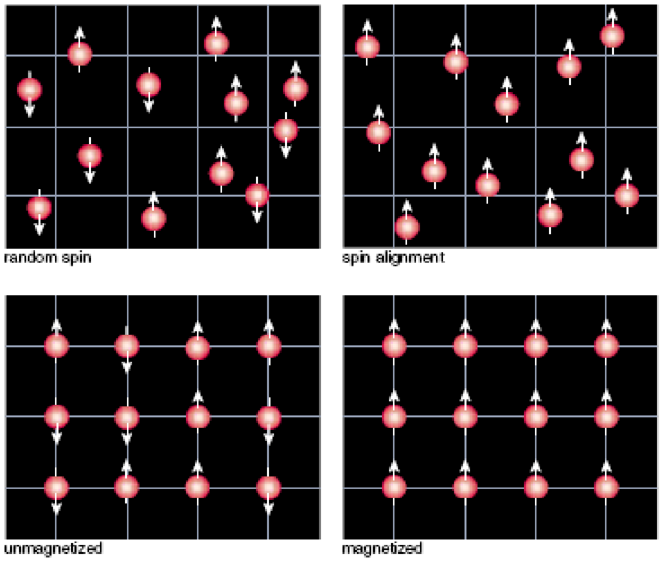
Introduction

Spintronics or spin electronics is an emerging field of basic and applied research in physics and engineering that aims to exploit the role played by electron spin in solid state materials. The spin-electronics is otherwise called as spintronics, where the spin of an electron is controlled by an external magnetic field and polarize the electrons. These polarized electrons are used to control the electric current. The goal of spintronics is to develop a semiconductor that can manipulate the magnetism of an electron. Once we can add the spin degree of freedom to electronics, it will provide significant versatility and functionality to future electronic products. Magnetic spin properties of electrons are used in many applications such as magnetic memory, magnetic reading (read, write heads), etc. [1]

The realization of semiconductors that are ferromagnetic above room temperature will potentially lead to a new and generation of spintronic devices with revolutionary electrical and optical properties. The field of spintronics was born in the late 1980s with the discovery of the 'giant magetoresistance effect'. The giant mgnetoresistance (GMR) effect occurs when a magnetic field is used to align the spin of the electrons in the material, including a large change in the large resistance of the material. A new generation of miniature electronic devices like computer chips, light emitting devices for displays, and sensors to detect radiation, air pollutants, light and magnetic fields are possible with the new generation of Spintronic materials. [1]

The electronic devices, information is stored and transmitted by the flow of electricity in the form of negatively charged subatomic particles called electrons. The zeros and ones of computer binary code are represented by the presence and absence of electrons within a semiconductor or other material. In Spintronics, information is stored and transmitted using another property of electrons called spin. Spin is the intrinsic angular momentum of an electron, each electron acts like a tiny bar magnet, like a compass needle, that points either up or down to represent the spin of electron. Electrons moving through a non magnetic material normally have random spins, so the net effect is zero. External magnetic fields can be applied so that the spins are aligned (all up or all down), allowing a new way to store binary data in the form of one's (all spins up) and zeros (all spins down). The effect was first discovered in a device made of multiple layers of electrically conducting materials: alternating magnetic and non magnetic layers. The device is known as a "spin valve" because when a magnetic field was applied to the device, the spin of its electrons went from all up to all down, changing its resistance so that the device acted like a valve to increase or decrease the flow of electrical current, called Spin Valves.[1]



Fundamentals spin-

I. In addition to their mass, electrons have an intrinsic quantity of angular momentum called spin, almost of if they were tiny spinning balls.

II. Associated with the spin is magnetic field like that of a tiny bar magnet lined up with the spin axis.

III. Scientists represent the spin as a vector. For a sphere spinning “west to east”, the vector points “north or up”. It points “south or down” for the spin from “east to west “

IV. In a magnetic field, electrons with “spin up” and “spin down” have different energies

V. In an ordinary electronic circuit the spins are oriented at random and have no effect on current flow.

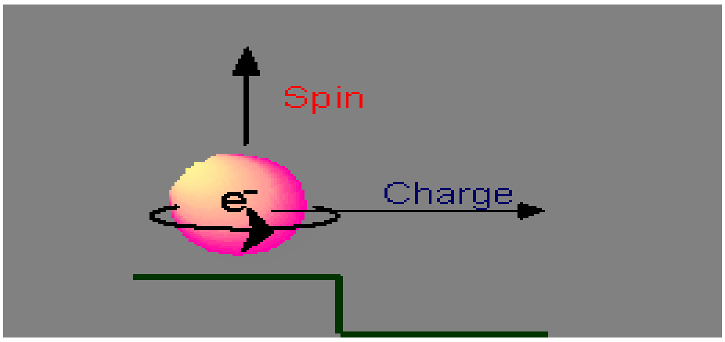


Fig:- electron spining

Why we need spintronics:-

The miniaturization of microelectronic components by roughly a factor of 40 has taken place from the early days of integrated circuits, starting around 1970. Over this time, microelectronics has the advanced from the first integrated circuits to present day computer chips containing 100 million transistors. It is now well recognized that further shrinking of the physical size of semiconductor electronics will soon approach a fundamental barrier. The fundamental physical laws that govern the behavior of transistors will preclude them from being shrunk any further and packed in even greater number on computer chips. The continual shrinking of transistors will result in various problems related to electric current leakage, power consumption and heat. [2]

On the other hand, miniaturization of semiconductor electronic devices is making device engineers and physicists feel the looming presence of quantum mechanics- a brilliant physics concept developed in the last century – where counterintuitive ideas such as wavelike behavior, is more dominant for 'particles' such as the electron. Electron spin is, after all, a quantum phenomenon. Many experts agree that Spintronics, combined with nanotechnology would offer the best possible solution to the problems associated with miniaturization mentioned above. Nanoscience and nanotechnology involve the study of extremely tiny devices and related phenomena on a spatial scale of less than one thousandth the diameter of a human hair or roughly half the diameter of a DNA molecule. [2]

Theory

Different type of spintronic devices formed by the general magneto resistance effect are given below

1. Semiconductor spintronics
2. Spin transistors
3. Spintronics scanner, etc.

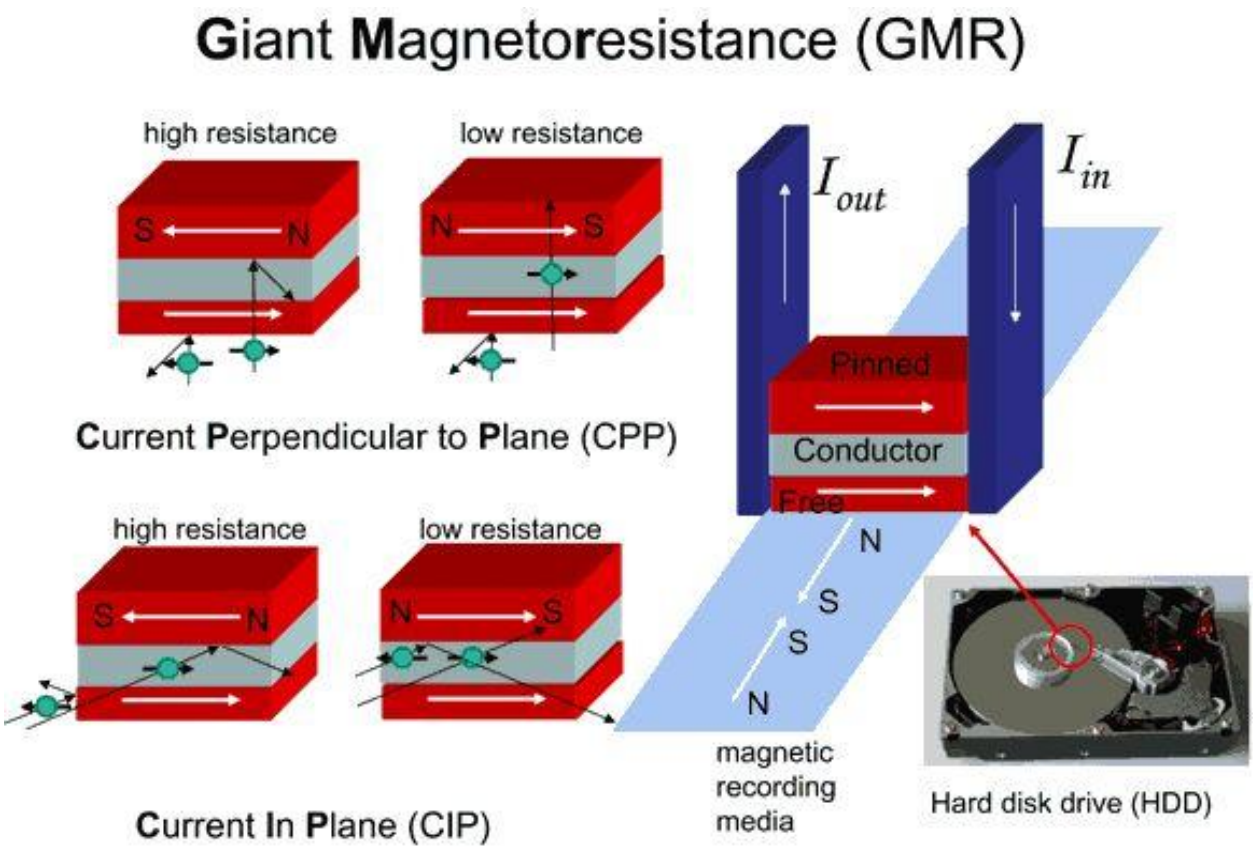
Spintronic devices based on the metal oxide semiconductor technology was the first field effect spin transistor proposed in 1989 by Suprio Datta and Biswajit Das of Purdue University.

Semiconductor spintronics

In spite of the rapid advances in metal-based Spintronics devices (such as GMR devices), a major role for researches has been to find novel ways to generate and utilize spin polarized currents in semiconductors. These include the investigation of spin transport in semiconductors and exploration of possibilities for making semiconductors function as spin polarizers and spin valves. This is important because semiconductor-based Spintronics devices can easily be integrated with traditional semiconductor technology; they also can serve as multipurpose devices. Further spin in semiconductors can be more easily manipulated and controlled. Visionaries claim that a merger of electronics, photonics and magnetic will provide novel spin based multifunctional devices such as spin-FETs, spin-LED, spin-RTDs, optical switches operating at terahertz frequencies, modulators, quantum computation, etc. This progress in these developments of course, crucially depends on our understanding and control of the spin degrees of freedom in semiconductors, semiconductors Heterostrucutres, and ferromagnets .[2]

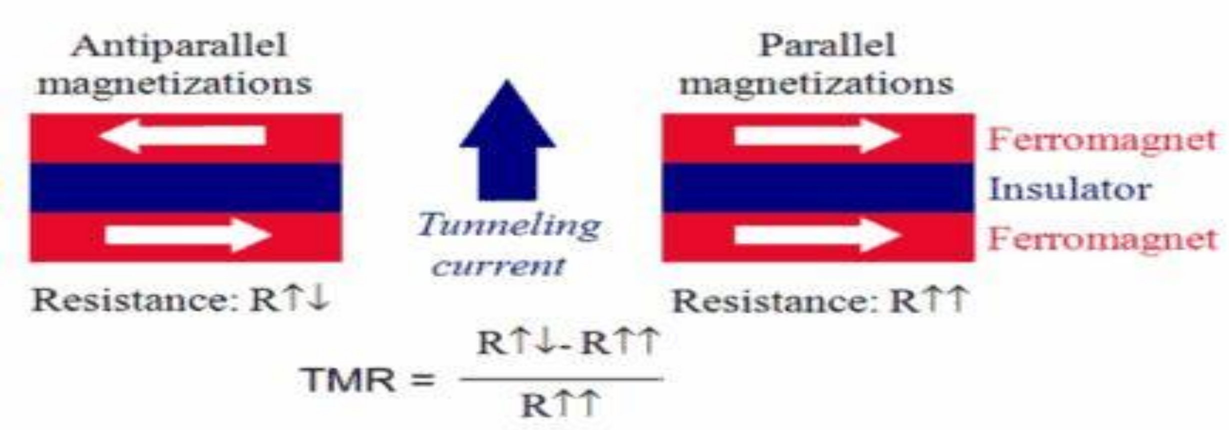
(a)GMR----

Spintronics burst on the scene in 1988 when French and German physicists discovered a much more powerful effect called 'giant magnetoresistance'(GMR). It results from electron spin effects in ultra –thin 'multilayers' of magnetic and nonmagnetic materials alternatively which cause huge changes in their electrical resistance when a magnetic field applied.GMR is 200 times stronger than ordinar magnetoresistance. The current passes through the layers consisting of spin-up and spin-down electrons. Those oriented in same direction as the electron spin in a magnetic layer pass through quite easily while those oriented in the opposite direction are scattered. If the orientation of one of the magnetic layers can be easily be changed by the presence of magnetic field then the device will act as a filter, or 'spin valve', letting through more electrons when the spin orientations in the two layers are the same and fewer when orientations are oppositely aligned. The electrical resistance of the device can therefore be changed dramatically.



(b)TMR-

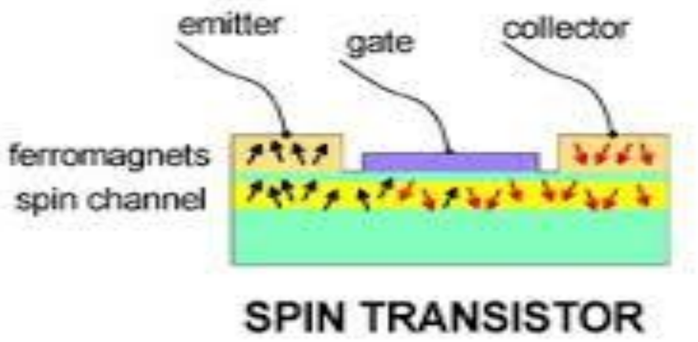
Tunel magnetoresistance (TMR) is a magneto resistive effect that occurs in magnetic tunnel junction. It consist of 2 Ferro magnets, separated by insulating metal oxide layer. Here the insulator should be only a few atomic layer thick, so that there is a significant probability that electrons can quantum mechanically tunnel through the insulating barrier. If the insulating wire is thin enough (typically a few nano meters) electrons can tunnel from one ferro-magnet to the other. It is similar to GMR spin valve except that a very thin layer is sandwitched between magnetic layers instead of metal layer.



Applications of spintronic devices----

1. Spin transistor----

The basic idea of a spin transistor, as proposed by Suprio Datta and Biswajit Das is to control the spin orientation by applying a gate voltage . A spin FET, as depicted below, consists of ferromagnetic electrodes and a semiconductor. The source and drain electrodes are ferromagnetic metals.[2] The spin polarized electrons are injected from the FM source electrode, and after entering the semiconductor channel they begin to rotate. The rotation is caused by an effect due to “spin orbit coupling’ that occurs when electrons move through the semiconductor crystal in the presence of an electric field. The rotation can be controlled, in principle, by an applied electric field through the gate electrode. If the spin orientation of the electron channel is aligned to the FM drain electrode, electrons are able to flow into the FM drain electrode. If the spin orientation is flipped in the electron layer, electrons cannot enter the drain electron. In this way, with the gate electrode the rotation of the electron spin can be controlled. Therefore, in a spin-FET the current flow is modified by the spin precession angle.



One advantage of spin transistor over regular transistor is that the spin states can be detected and altered without necessarily requiring the application of electric current. This allows for detection of hardware that are much smaller but even more sensitive than today’s devices, which relay on noisy amplifiers to detect the minute charges used on today’s data storage devices. The potential end result is devices that can store more data in less pace and less power consumption, using less costly materials.

The second advantage of spin transistors is that the spin of an electron is semi-permanent and can be used as means of creating cost-effective non volatile solid state storage that does not require the constant application of current to sustain. It is one of the technologies being explored for Magnetic Random Access Memory (MRAM), which produce the computers random access memory and are being

for use of magnetic RAM. This memory is superfast and information stored o it is held in place after the computer is power off as much like hard disk.

2. STAG: Spintronic- Tape Architecture for GPGPU Cache Hierarchies

The use of General-purpose Graphics Processing Units for executing massively parallel workloads from various application domains. It is fueling an ever increasing demand for on-chip memory. Here, we have used STAG, a high density, design of energy- efficient GPGPU cache hierarchy using a new spintronic memory technology called Domain Wall Memory (DWM). DWMs offer benefits in density by storing multiple bits in the domains of a ferromagnetic nano wire, which is used for logically resembling a bit-serial tape [3]. However, this memory structure also leads to a unique challenged that —the data should be operated by performing "shift" operations, resulting in variable and potentially higher access burdens. To overcome this challenge, STAG uses a number of architectural techniques; ---

(i) Different DWM bit-cells are employed by a hybrid cache organization to observe the different memory arrays all in the GPGPU cache hierarchy [4],

(ii) A clustered, bit-interleaved organization in which the bits in a cache block are spread across a cluster of DWM tapes, parallel access is allowed.

(iii) Tape head management policies which predictively configure DWM arrays to slow down the expected number of shift Operations for subsequent accesses [5]

6. Spintronics For hardware security

In this section we have presented the motivation behind exploring application of spintronics in hardware security. The manufacturing of the present day IC are outsourced to external companies. Under this business model the design is risked to tampering and cloning given by the third party breaching the Intellectual Property. Unique keys are generated by the ICs which are then stored on the on-chip nonvolatile memory. However, adversaries can open the secret key through Reverse Engineering (RE). In order to correct these issues an auxiliary circuit i.e. Physically Unlovable Function (PUF) is coordinated in the authentic chips. Designing PUFs are used to exploit the bodily properties of the chip (e.g., process) to make its unique identification key. The downside of CMOS based circuits are area and power overhead, affectability to environmental fluctuations, limited randomness and entropy given by the Silicon substrate [6]. We note that spintronics is another possible candidate that possesses an untapped source of entropy in the system rather than having an energy-efficiency of higher order of magnitude than CMOS.

(i) Quantum computation:

Spin-based quantum computer (QC) is the most revolutionary concept among all the possible spintronics devices [7,8,9]. In QC, either electron spin or nuclear spin is used as the building blocks. The spin-up and spin-down state of an electron or a nucleus provide the quantum bit (qubit), analogous to '0' or '1' in a classical computer (CC). However, spin which obeys the laws of quantum mechanics cannot have only up and down states, but also arbitrary superposition of these two states. This inherent parallelism and other quantum mechanical properties such as entanglement and unitary evolution distinguish QC from classical computer (CC).

A central issue of quantum computing is to develop algorithms that take advantage to process information faster than the best classical computers can. Unlike the CC, the QC handle more inputs with less number of qubits, so quantum computation algorithm are much faster. The increased number of input not only leads to an enormous increase in computation time but also limits the hardware, which makes the CC behind [10].

The main goal of quantum computer is to change the exponential CC time into polynomial QC time. Closest to this goal comes up till now is Shor's Algorithm [8]: it would allow a quantum computer to find the prime factors of a large number in polynomial time. For classical computers, no such algorithm is known: finding the factors, *e.g.*, a thousand-digit number would take much longer time than the age of the universe using today's classical computers, while a quantum computer might find them within seconds. The second major quantum algorithm is Grover's Algorithm [11] which finds a marked item in an unsorted database containing N entries with about square root of N queries to the database. On a classical computer, the best algorithm needs on the order of N queries.

In search of appropriate model for a QC, many proposals have been put forward. There are proposals [12,13,7,14] suggesting quantum dot-trapped electron spin as qubits. In this, a single electron is trapped in a gated horizontal GaAs quantum dot, with pulsed local magnetic field and inter-dot gate voltage governing the single qubit and two qubit operation. Vrijen *et al* [15] proposed that donor electrons replace the irreversible and classical, so that the QC operation will be disrupted. It is also believed [15] that large-scale experimental quantum computing would be impossible because of the fragile nature of quantum information. However, this concern has been largely resolved by the development of quantum error correction (*i.e.* quantum information can be encoded in such a way that potential error can be detected and corrected) and fault-tolerant quantum computation. The theory of quantum error correction and fault-tolerant quantum computing has been developed to overcome this difficulty [16-17].

3 **Spintronic Scanner**

Cancer cells are the somatic cells which are grown into abnormal size. The Cancer cells have different electromagnetic sample when compared to normal cells. For many types of Cancer, it is easier to treat and cure the Cancer if it is found early. There are many different types of Cancer, but most Cancers begin with abnormal cells growing out of control, forming a lump that's called a tumor. The tumor can continue to grow until the Cancer begins to spread to other parts of the body. If the tumor is found when it is still very small, curing the Cancer can be easy. However, the longer the tumor goes unnoticed, the greater the chance that the Cancer has spread. This makes treatment more difficult. Tumor developed in human body, is removed by performing a surgery. Even if a single cell is present after the surgery, it would again develop into a tumor. In order to prevent this, an efficient route for detecting the Cancer cells is required. Here, in this paper, we introduce a new route for detecting the Cancer cells after a surgery. This accurate detection of the existence of Cancer cells at the beginning stage itself entertains the prevention of further development of the tumor. This spintronic scanning technique is an efficient technique to detect cancer cells even when they are less in number. An innovative approach to detect the cancer cells with the help of Spintronics: The following setup is used for the detection of cancer cells in a human body:

(a) Polarized electron source

(b) Spin detector

(c) Magnetic Field

Spintronics, in future---

Today everyone already has a spintronic device on their desktop, as all modern computers use the spin valve in order to read and write data on their hard drive. It was followed immediately by the discovery of Tunneling Magnetoresistance (TMR) leading to the magnetic tunnel junction that has been utilized for the next generation computer memory known as Magnetic Random Access Memory (MRAM), another spintronic device for computers. Therefore, the initial driving force for spintronics has been the improvement of computer technology. At present the research has been concentrating on the fabrication of spin transistors and spin logics devices integrating magnetic and semiconductors, with the aim of improving the existing capabilities of electronic transistors and logics devices so that the future computation and thus the future computer could become faster and consume less energy.

There are five main areas in spintronics:

1) Understanding the fundamental physics, such as spin-dependant transports across the magnetic/ semiconductor interfaces and spin coherence length in semiconductors.

2) Synthesising suitable spintronic materials with Curie temperatures above room temperature, large spin polarisation at the Fermi level and matching conductivity between the magnetic and semiconductor materials.

3) Fabricating devices with nanometre feature sizes and developing new techniques for mass production.

4) Integrating spin-devices with current microelectronics and computing.

5) In medical science to detect the cancer cells by spintronic scanner.

Conclusion

In my project, we have reviewed recent advances in spin-based electronics devices and quantum computation. The progress in this field is extremely rapid, as evident by the large numbers and quality of scientific studies, and also by the growing number of applications. However, the progress towards the understanding and implementation of spin degree of freedom in metallic multilayer and semiconductor is 'gaining momentum'. On the other hand, spintronics read head sensor are already impacting multibillion dollar industry and magnetic random access memory using metallic element will soon impact the industry.

However, current QC technology is limited to fewer than 10 qubits and the testing of simple algorithm [18], but quantum computation of the next generation, with 10-100 qubits is a challenging task that will be helpful in solving hard problems of quantum many body theory. Moreover, we need theoretical understanding of efficient algorithm that could enable us to understand the problems of finite system such as applicability of BCS model to mesoscopic state and nuclear systems. However, researchers are trying to find out low-lying spectrum of pairing models with long-range quantum computers of next generation (10-1000) qubits) [19].

Much remain to be understood about the behaviour of electron spin in materials for technological applications, but much has been accomplished. Now experimentalists are taking up the fundamental challenges of creating and measuring spin, understanding better transport of spin at interfaces and clarifying the types of errors in spin-based computational systems. Tackling these will help in developing new experimental tools and broaden considerably our theoretical understanding of quantum spin. However, the control of spin and its manipulation for ultra small structures is to be understood. We are working in this direction to understand the role of spins in ultra- small structures for example, carbon nanotube quantum dots. The proper understanding of these will be an entirely new world of spin technology with new capabilities and opportunities.

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