# *Spintronics: Fundamentals and Applications.*

***EE453 Project Report submitted by Anjum, Fakhar. (anjum171@hotmail.com) , Fall 2008***

## *Abstract:*

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. Spintronic devices make use of spin properties instead of, or in addition to electron charge to carry information, thereby offering opportunities for novel micro- and nano-electronic devices. [3] This article reviews the background and current status of this subject, and also some of the applications of Spintronics.

## *Overview:*

The spin-electronics also called 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 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 recording (read, write heads), etc. [1]

The realization of semiconductors that are ferromagnetic above room temperature will potentially lead to a new 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 magnetoresistance effect”. The giant magnetoresistance (GMR) effect occurs when a magnetic field is used to align the spin of electrons in the material, inducing a large change in the resistance of a 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]

In electronic devices, information is stored and transmitted by the flow of electricity in the form of negatively charged subatomic particles called electrons. The zeroes and ones of computer binary code are represented by the presence or 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 an electron**.** Electrons moving through a nonmagnetic 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 zeroes (all spins down). The effect was first discovered in a device made of multiple layers of electrically conducting materials: alternating magnetic and nonmagnetic layers. The device was 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]

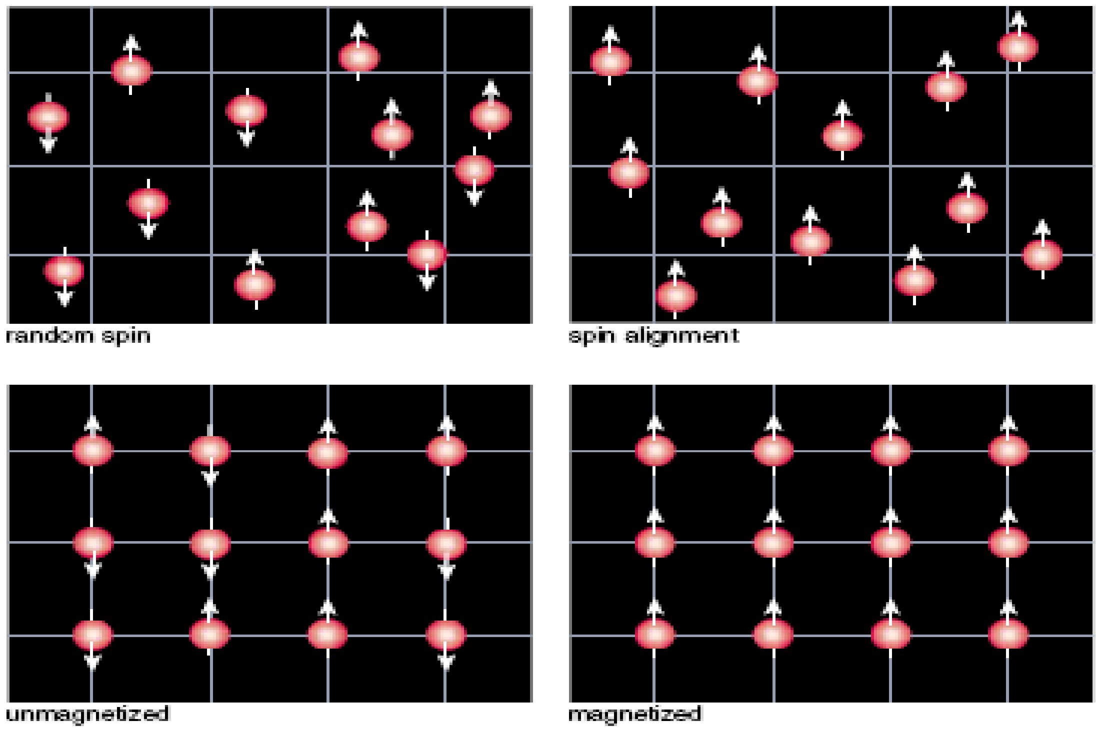


*Figure: 1. Spins can arrange themselves in a variety of ways that are important for Spintronics devices. They can be completely random, with their spins pointing in every possible direction and located throughout a material in no particular order (upper left). Or these randomly located spins can all point in the same direction, called spin alignment (upper right). In solid state materials, the spins might be located in an orderly fashion on a crystal lattice (lower left) forming a nonmagnetic material. Or the spins may be on a lattice and be aligned as in a magnetic material (lower right).* [2]

The first scheme of Spintronics device 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. In their device, a structure made from indium–aluminum-arsenide and Indium-gallium-arsenide provides a channel for two dimensional electron transport between two ferromagnetic electrodes. One electrode acts as an emitter and the other as a collector**.** The emitter emits electrons with their spins oriented along the direction of electrodes magnetization, while the collector acts as a spin filter and accepts electrons with the same spin only. In the absence of any change to the spins during transport, every emitted electron enters the collector. [1] This device is explained in further detail under the topic of spin transistors.

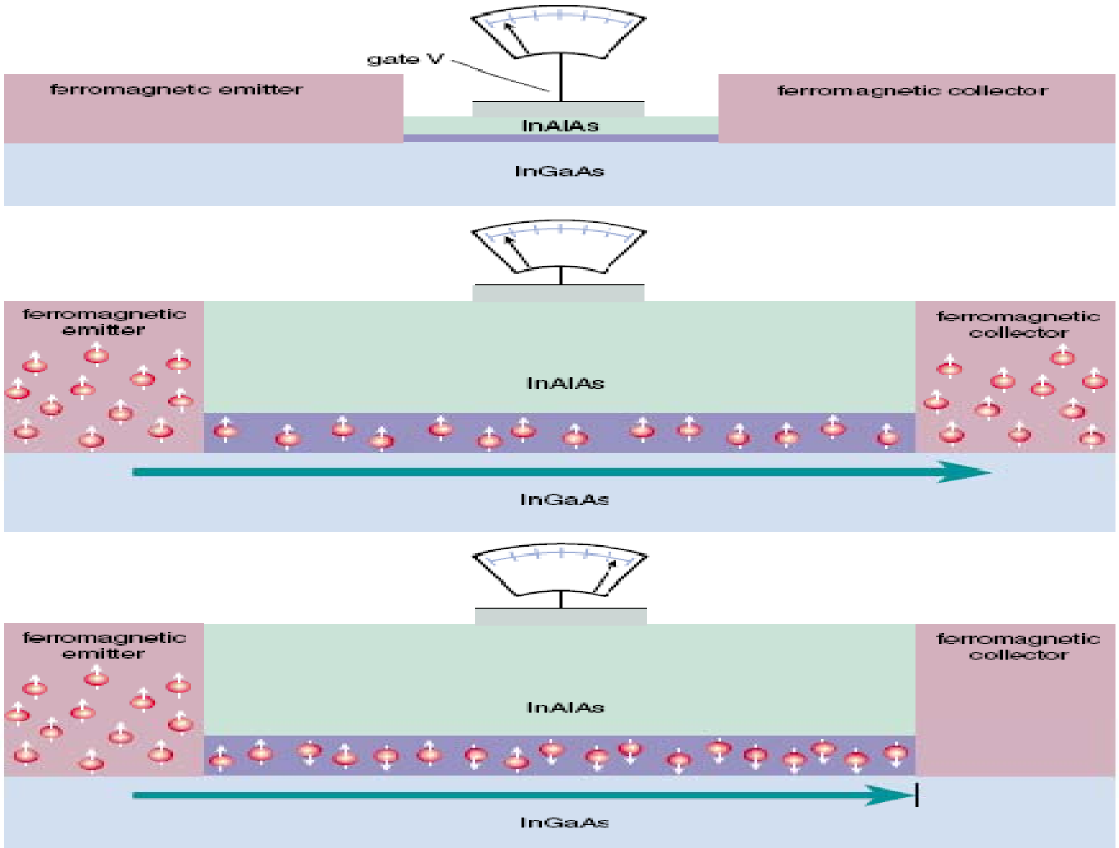


*Figure: 2. Datta-Das spin transistor was the first Spintronic device to be proposed for fabrication in a metal-oxide-semiconductor geometry familiar in conventional microelectronics. An electrode made of a ferromagnetic material (purple) emits spin-aligned electrons (red spheres), which pass through a narrow channel (blue) controlled by the gate electrode (gold) and are collected by another ferromagnetic electrode (top). With the gate voltage off, the aligned spins pass through the channel and are collected at the other side (middle). With the gate voltage on, the field produces magnetic interaction that causes the spins to precess, like spinning tops in a gravity field. If the spins are not aligned with the direction of magnetization of the collector, no current can pass. In this way, the emitter-collector current is modulated by the gate electrode. As yet, no convincingly successful application of this proposal has been demonstrated.* [2]

## ***Spintronic devices:***

Recording devices, such as computer hard disks, already employ the unique properties of magnetic materials. Data are recorded and stored as tiny areas of magnetized iron or chromium oxides. A “read head” can read this information by detecting minute changes in the magnetic field as the disk rotates underneath it. This induces changes in the head’s electrical resistance – also known as magnetoresistance. Spintronic devices, also known as magnetoelectronics, are expected to become the ideal memory media for computing and main operating media for future quantum computing. The first widely acknowledged breakthrough in Spintronics was the use of GMR, used in read heads of most hard drives already mentioned above. A "popular" device that exploits the Spintronics is, for example, the Apple iPod 60 GB. Measuring a little more than half an inch in thickness, this pocket filling device has a Spintronics based "read head"! [3]

Recent discovery of Tunneling Magnetoresistance (TMR) has led to the idea of a magnetic tunnel junction that has been utilized for the MRAM (Magnetic Random Access Memory). Here, one has two magnetic layers separated by an insulating metal-oxide layer. Electrons are able to tunnel from one layer to the other only when magnetizations of the layers are aligned in the same direction. The resistance is otherwise very high, in fact, 1000 times higher than in the standard GMR devices, known as "spin valves". Spintronic devices, combining the advantages of magnetic materials and semiconductors, are expected to be fast, non-volatile and consume less power. They are smaller than 100 nanometers in size, more versatile and more robust than the conventional ones making up silicon chips and circuit elements. The potential market is expected to be worth hundreds of billions of dollars a year. [3]

## ***Why 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 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. [3]

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. [3]

## ***Semiconductor Spintronics:***

In spite of the rapid advances in metal-based Spintronics devices (such as GMR devices), a major focus for researchers 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 the 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 multi-functional devices. Further, spins in semiconductors can be more easily manipulated and controlled. Visionaries claim that a merger of electronics, photonics, and magnetics will provide novel spin-based multifunctional devices such as spin-FETs (field-effect transistors), spin-LEDs (light-emitting diodes), spin-RTDs (resonant tunneling devices), optical switches operating at terahertz frequencies, modulators, quantum computation, etc., just to name a few. The progress in these developments of course, crucially depends on our understanding and control of the spin degrees of freedom in semiconductors, semiconductor heterostructures, and ferromagnets. [3]

## ***Spin transistor:***

The basic idea of a spin transistor, as proposed by Suprio Datta and Biswajit Das (Purdue University, USA) is to control the spin orientation by applying a gate voltage. A spin-FET, as depicted below, consists of ferromagnetic electrodes and a semiconductor channel that contains a layer of electrons and a gate electrode attached to the semiconductor. The source and drain electrodes are ferromagnetic (FM) metals. [3]

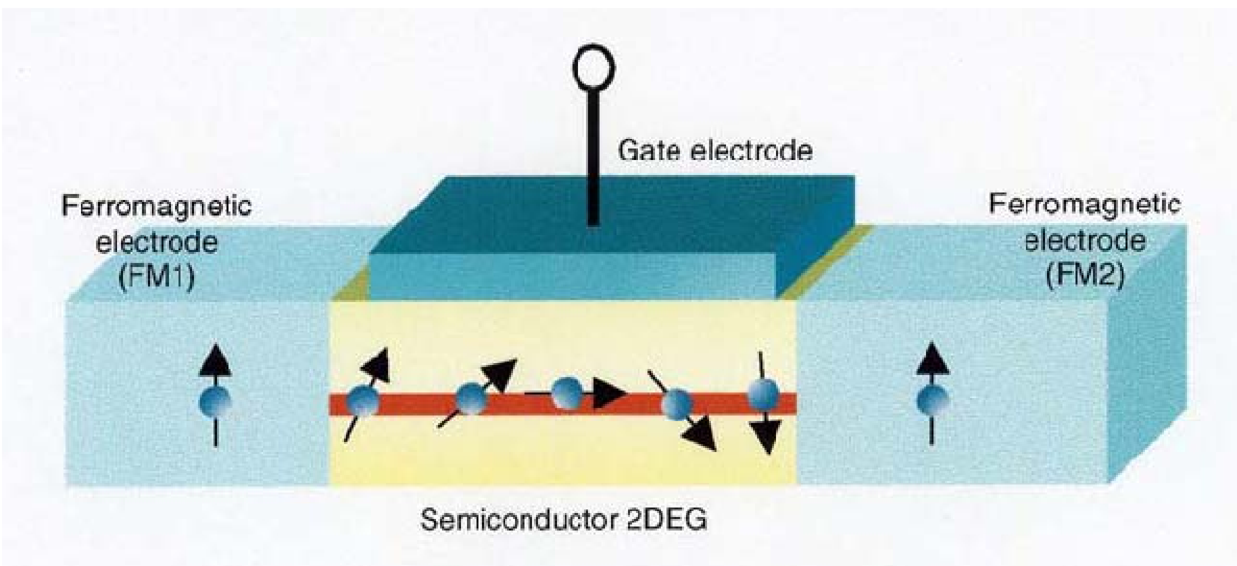


*Figure: 3 Datta-Das spin Transistor.*

The spin-polarized electrons are injected from the FM source electrode (FM1), 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. However, if the spin orientation is flipped in the electron layer (as in the figure above), electrons cannot enter the drain electrode (FM2). 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. Since the spin-FET concept was published in 1990, there has been a world-wide effort to develop such a transistor. The success of such a project crucially depends on efficient injection of spin currents from a ferromagnetic metal into a semiconductor, a seemingly formidable task. Intense research is under way to circumvent this problem by using (Ferro) magnetic semiconductors such as GaMnAs. [3]

## **Quantum dots: Spin-based computers:**

Modern nanofabrication techniques and materials engineering have reached a level where it is now possible to fabricate advanced semiconductor devices at atomic scales. The most remarkable ones are the 'quantum dots' in which electron motion is quantized along all directions and conducting electrons are confined within the nanometer distances.[4] The dots contain typically one to several hundred electrons and experiments have shown effective control over both the charge and spin degree of freedom of these confined electrons. Quantum dots have been found to be very useful as electronic and optical devices such as the quantum-dot laser, memory chips, and in quantum cryptography, quantum computer, etc. It has been proposed that the spin of an electron confined to quantum dots can be used as quantum bits and an array of quantum dots could serve as a quantum computer. In principle, a computer that processes the quantum states instead of conventional classical information will be able to solve problems for which there is no efficient classical algorithm. Quantum operations in the quantum dots would be possible by coupling electron spins in neighboring quantum dots. Fundamental understanding of the role of electron spins in quantum-confined structures is crucial in this effort, and my research group is actively involved in this endeavor. [3]

## ***Electron (spin) transport in DNA:***

Why DNA? – As mentioned above, in the face of continued miniaturization of components and circuitry in microelectronics, conventional semiconductor microelectronics is rapidly approaching its useful miniaturization limits due to some fundamental limitations of large-scale photolithography and the expected failure of semiconductor physics in nanometer-scale components. For an alternative approach, one might look in nature, in particular in biology, where biological molecules are known to self-assemble with nanometer scale resolution and possess some unique qualities that might be crucial for nanoscale fabrication: these include

(I) highly effective molecular recognition processes.

(ii) Self-assembly processes coupled to mechanisms that are responsible for proof-reading during the construction process.

(iii) Billions of years of evolution that has optimized the efficient assembly processes.

DNA, the molecule of life is particularly attractive in this respect. In humans, the DNA molecule consists of two ribbon-like strands (double helix) that wrap around each other, resembling a twisted ladder. [3]

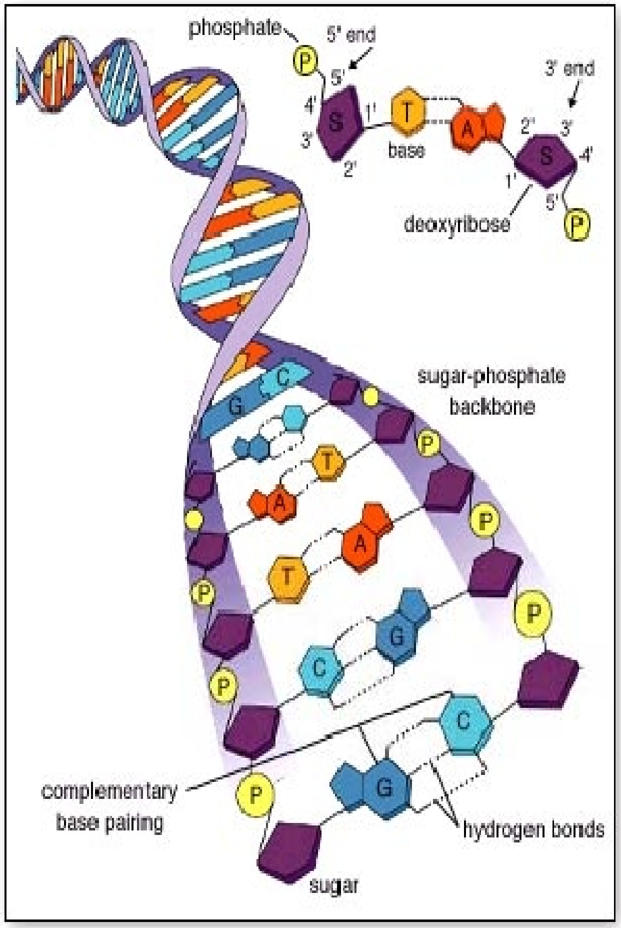


Figure: 4 A diagram of the general structure of DNA. It shows the famous overall double helix. And it shows the four bases (A, T, G and C) -- which are the "information". At each rung along the DNA ladder is a base pair. Each pair is either A with T or G with C; that is, one strand precisely determines the other strand -- and that indeed is the key to how DNA replicates.

The steps of the ladder are made of four bases A (adenine), T (thymine), G (guanine) and C (cytosine). Bases of DNA come as a pair and always ‘A’ pairs with ‘T’ and ‘G’ with ‘C’. Base pairs are held together by hydrogen bonds. The A-T pair has two hydrogen bonds while the G-C pair contains three hydrogen bonds. The sugar-phosphate backbones form the sides of the ladder. Double-stranded DNA has a diameter of ~2nm and a helical pitch of 10.5 bases with 0.34 nm separation of the plane in which adjacent base pairs are located. Each phosphate group in the sugar-phosphate backbone of the DNA carries a negative charge. In fact, the DNA double helix is one of the most highly-charged polymers with a base charge density of one charge per 0.17 nm. In recent years, electronic transport through DNA has been the subject of intense research activity. The reason is twofold: understanding of charge migration in DNA is important because of its biological implications, in particular, for oxidative damage and repair of DNA and the other is the potential application of DNA as an important part in molecular electronics. [3]

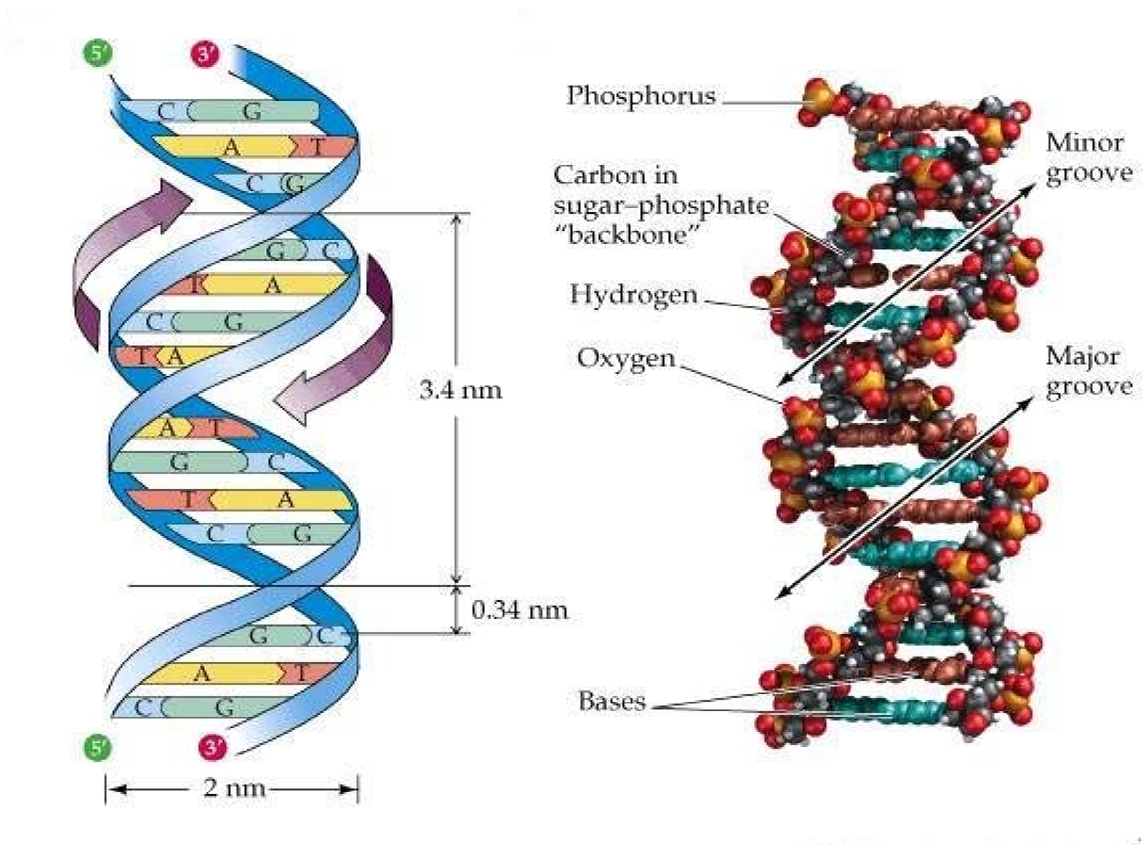


Figure: 5 Structure of DNA with dimensions.

Compared to semiconductor materials, electron transport in DNA would be faster because of less scattering events which will lead to longer spin lifetime. This would be particularly useful for spin transport in DNA. It is already established that electron transfer along DNA occurs on length scales of up to a few nanometers. The conductivity of DNA on larger length scales has been an active area of research study because here the goal is to manipulate DNA in the atomic scale and make DNA devices using currently available techniques. Electronic properties of DNA, the charge and also the spin transport in DNA are topics of major activity in my research group. [3]

## ***Expectation for the future:***

Spintronics is one of the most challenging and fascinating areas in nanotechnology. Its impact is felt both in fundamental scientific research and industrial applications. To cope with its rapid progress in pure and applied science, coordinated efforts by researchers from diverse fields including physics, chemistry, biology, materials science and engineering are absolutely necessary. From today's read heads to quantum information processing in the future, the electron spin has exhibited the limitless potential to impact our lives as we look through the magical quantum world at the nanoscale, a world that is not much different from an Alice-in-wonderland world that plays by its own rules. We are yet to understand fully most of those rules, but we are making significant progress through research in Spintronics. **[5]**

## ***Conclusion:***

The GMR is the background to switch from the "traditional" electronic to the spin based electronics. Spintronic has great potentiality for applications and it is the beginning of its journey. The realization of semiconductors that are ferromagnetic above room temperature will potentially lead to a new generation of spintronic devices with revolutionary electrical and optical properties. [6]

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