Micro Magnetics Sensible Solutions

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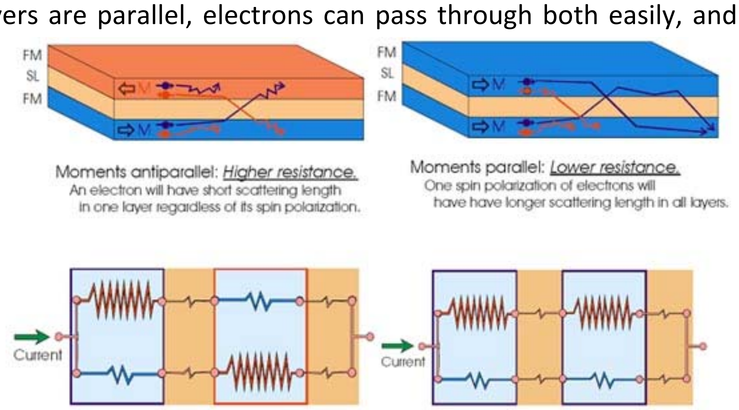
What is Spintronics? a.k.a Magnetoelectronics, Spin Electronics, or Spin-based Electronics.

The age of electrically-based devices has been with us for more than six decades. With more and more electrical devices being packed into smaller and smaller spaces, the limits of physical space will prevent further expansion in the direction the microelectronics industry is currently going. Also, volatile memory, which does not retain information upon being powered off, is significantly hindering ultrafast computing speeds. However, a new breed of electronics, dubbed “spintronics,” may change all of that.

Instead of solely relying on the electron’s negative charge to manipulate electron motion or to store information, spintronic devices would further rely on the electron’s spin degree of freedom, the mathematics of which is similar to that of a spinning top. Since an electron’s spin is directly coupled to its magnetic moment, its manipulation is intimately related to applying external magnetic fields. The advantage of spin-based electronics is that they are very nonvolatile compared to charge-based electronics, and quantum-mechanical computing based on spintronics could achieve speeds unheard of with conventional electrical computing. Spintronics, also called magnetoelectronics, spin electronics, or spin-based electronics, is an emerging scientific field. The research on spintronics can be divided into the following subfields.

Spin Valve with Giant Magnetoresistance

One spintronic device that currently has wide commercial application is the spin-valve. Most modern hard disk drives employ spin-valves to read each magnetic bit contained on the spinning platters inside. A spin-valve is essentially a spin “switch” that can be turned on and off by external magnetic fields. Basically, it is composed of two ferromagnetic layers separated by a very thin non-ferromagnetic layer. When these two layers are parallel, electrons can pass through both easily, and when they are antiparallel, few electrons will penetrate both layers.



The spin-valve acts as a filter for one spin polarization that can be switched on and off.

The principles governing spin-valve operation are purely quantum mechanical. Generally, an electron current contains both up and down spin electrons in equal abundance. When these electrons approach a magnetized ferromagnetic layer, one where most or all contained atoms point in the same direction, one of the spin polarizations will scatter more than the other. If the ferromagnetic layers are parallel, the electrons not scattered by the first layer will not be scattered by the second, and will pass through both. The result is a lower total resistance (large current). However, if the layers are antiparallel, each spin polarization will scatter by the same amount, since each encounters a parallel and antiparallel layer once. The total resistance is then higher than in the parallel configuration (small current).

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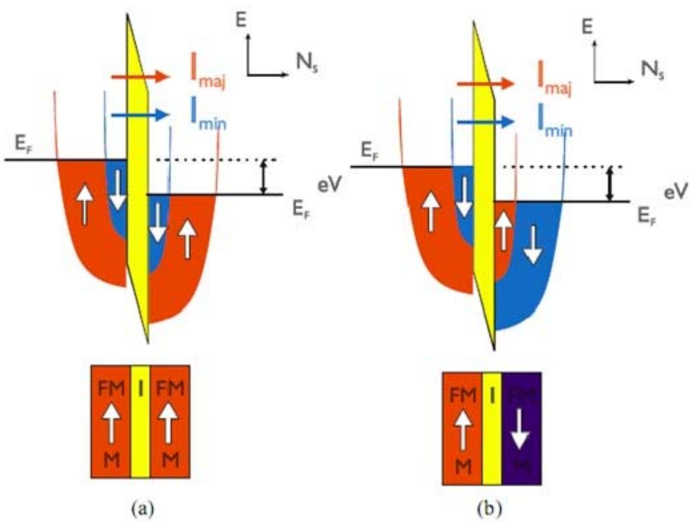
Thus, by measuring the total resistance of the spin valve, it is possible to determine if it is in a parallel or antiparallel configuration, and since this is controlled by an external magnetic field, the direction of the external field can be measured. Since each bit in a hard drive either points in one direction or the other, their orientation can easily be determined with a device using this mechanism. The two physicists who discovered the giant magnetoresistance (GMR) effect in 1986 received the 2007 Nobel Prize in Physics.

Magnetic Tunneling Junctions (MTJs)

Another type of magnetoresistance that is governed by similar quantum mechanical laws is being exploited as a better mechanism for a much more sensitive magnetic field sensor. Like GMR, tunneling magnetoresistance (TMR) in a multilayer junction filters one spin polarization over another depending on the orientation of an external magnetic field. However, the two technologies differ in their exact filtering mechanism.



In a magnetic tunneling junction, the density of states of both plates determines whether a large current (a) or small current (b) tunnels through.

In a magnetic tunneling junction (MTJ), the device which employs the tunneling magnetoresistance effect, two magnetic layers are separated by a thin insulating layer. If a bias is placed across the junction, electrons will tunnel through depending on the relative orientation of the two ferromagnetic plates.

In a magnetized ferromagnet, the density of states (DoS) differs between up and down spins, causing the intrinsic magnetization of the material. Because of this, the magnet has more states available to one spin orientation than another. When a bias voltage is placed across the barrier, electrons will tunnel across depending on the availability of free states for its spin direction. Thus, if two magnetic layers are parallel, a majority of electrons in one will find many states of similar orientation in the other, causing a large current to tunnel through and a lowering of overall resistance. However, if they are antiparallel, both spin directions will encounter a bottleneck in either of the two plates, resulting in a higher total resistance.

TMR effect is larger than GMR effect by about a factor of 10. Currently, TMR MTJ sensors have been used in hard drives. Micro Magnetics, Inc. is the leading company worldwide in the manufacturing and marketing of ultrasensitive MTJ magnetic sensors.

Spin Torque Effect

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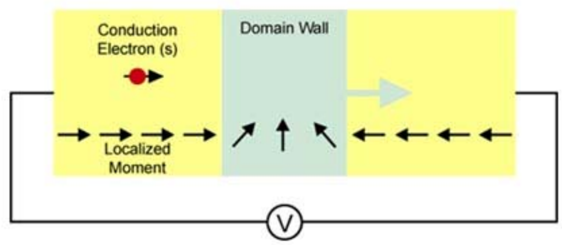
When a current of electrons passes through a magnetized ferromagnetic layer, it becomes spin polarized in one direction, much like the polarization of light through a filter. However, spin is the quantum mechanical analogue of angular momentum, and when a current of electrons gets spin polarized by a ferromagnet, a small transfer of angular momentum happens between the current and the magnet.

Classically, when the angular momentum of any object changes, it experiences a torque. Much in the same fashion, the moment of the ferromagnetic layer experiences a torque when polarizing the spins of a current. Thus, by sending a strongly polarized current through a magnetic layer with a moment in a different direc tion, it is possible to place a torque on the layer's magnetic moment and change its direction. This changing of the moment by sending a polarized current is called the spin-torque effect, or spin transfer switching. Before the spin torque effect was discovered, one could change the magnetic moment direction of a magnet by applying a magnetic field, like a compass needle rotating in Earth's magnetic field. Now, it is possible to change the direction of the moment by sending a spin-polarized electrical current through the magnet.

Spin transfer switching is currently being looked at as an alternative method to write data in magnetic random access memory (MRAM). Currently, data is written by reorienting the magnetic moment of a ferromagnetic layer by way of the magnetic field produced by a current. However, spin transfer switching would use much smaller currents to write data, and thus, it would be a more efficient technique. MRAM is non-volatile, unlike semiconductor DRAM devices. It can potentially unify the functions of DRAM and hard drive, and become a "Universal Memory" device, which is the holy-grail of data-storage technology. Micro Magnetics' scientists and engineers are undertaking various research and development projects advancing MRAM technology.



A current of spin-polarized electrons can change the direction of the moment of a ferromagnetic plate

The spin-torque effect can also be taken advantage of in the design and realization of ultrahigh frequency (RF) microwave devices such as frequency standard devices, DC to AC converters, microwave sources, antennas, and isolators.

Spin Injection into Semiconductors

The goal of spintronics research is to eventually relieve present information technology from solely relying on the charge of electrons. The spin degree of freedom of an electron has shown to be a very viable candidate to save the microelectronics industry from the results of "Moore's Law," which describes a trend of electrical components getting increasingly smaller, eventually reaching atomic scales. Though much progress has been made, a final obstacle needs to be overcome for spintronics to emerge as dominant technology. Spintronics is highly energy efficient, and spintronic devices generate less heat in operation than semiconductor devices. This unique property may extend the life of "Moore's Law" by having higher integration levels without astronomical heat generation.

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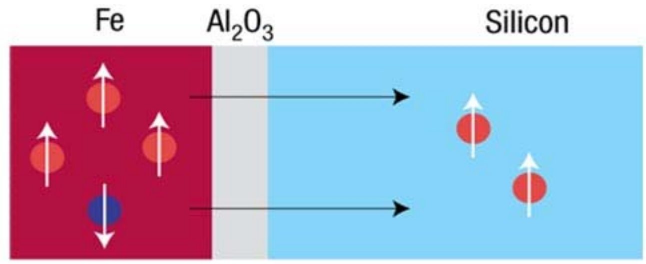


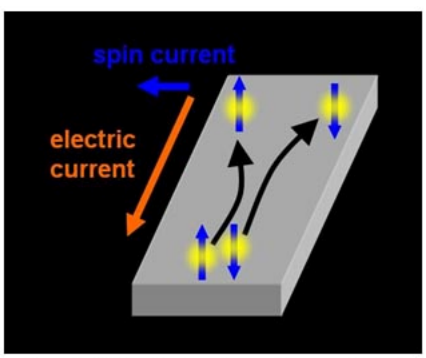
Injection of spin-polarized currents into semiconductors is a tough obstacle.

Since nearly all electronic components currently rely on semiconductors, namely Silicon, it would make sense to interface any new spintronics technology with semiconductors as well. However, maintaining spin polarization in a semiconductor can prove to be quite difficult. The major problem is that it is hard to form good atomic interface between a ferromagnetic metal and a semiconductor. Poor interfaces can cause the electron spins to be randomized in direction when electrons transit through the interface.

One can eliminate the interface problem by making semiconductors into ferromagnets. Unfortunately, a semiconductor does not make a good ferromagnet in general. The magnetic semiconductors often work only at lower temperatures than room temperature, and they are not strongly magnetic.

Just recently, researchers have successfully injected spin polarized current into Silicon from a ferromagnet. Since Si has no nuclear spin, there are no hyperfine interactions, resulting in very high spin preservation for electrons inside the semiconductor. This “final hurdle” may finally allow spintronics to emerge as force in electronic technology. More research is needed in achieving high quality spin injection techniques.

Spin Hall effect



The spin-Hall effect can be used to manipulate differently spin-polarized electrons.

In order to realize spintronics as a fully operational technology, the ability to manipulate spin polarized electrons within a conductor is necessary. A phenomenon called the spin Hall effect may be the solution.

In the regular Hall effect, if a magnetic field is placed perpendicular to the direction of current flow in a conductor, a bias voltage will be created perpendicular to both across the conductor. The reason for this is the electrons in the current interact with the magnetic field and experience a Lorentz force at right angles to the field and direction of current flow. They are pushed to one side of the conductor, and an electric field is created across the conductor.

In the spin Hall effect, a similar phenomenon occurs. Because the spin of an electron is coupled to its magnetic moment, if an electric field is placed perpendicular to the direction of current flow, the electrons’ spin degree of freedom interacts with the field and also experiences a Lorentz force. However, since electron spin can point either up or down, the two types of electrons will separate and move to opposite sides of the conductor. Although it was predicted almost 40 years ago, the spin Hall effect has received significant interest within the past decade.

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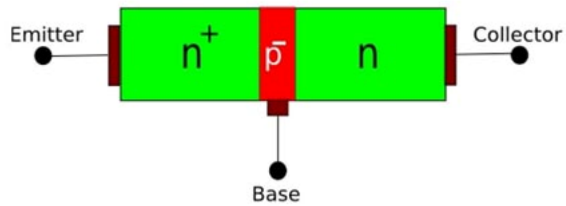
Magnetic (spin) transistors

In an ordinary transistor, specifically an n-p-n type transistor, two n-type semiconductors are separated by a p-type semiconductor. Near the n-p-n junction, a gate controls the voltage across the p-type semiconductor. When a voltage is placed across the p-type semiconductor, free electrons either are attracted towards the gate (base) or away from it, depending on the direction of the applied voltage. This lack or presence of gate electrons controls the flow of current between the two n-type semiconductors, allowing the transistor to occupy both on and off states.



A n-p-n type transistor.

The problem with electrically-based transistors is their volatility. When power is shut off, the electrons in the p-type semiconductor are no longer confined to a single region and diffuse throughout, destroying their previous on or off configuration. This is the reason why computers cannot be instantly turned on and off. However, a new type of transistor may change all of this.

In a magnetic transistor, magnetized ferromagnetic layers replace the role of n and p-type semiconductors. Much like in a spin-valve, substantial current can flow through parallel magnetized ferromagnetic layers. However, if, say, in a three layer structure, the middle layer is antiparallel to the two outside layers, the current flow would be quite restricted, resulting in a high overall resistance. If the two outside layers are pinned and the middle layer allowed to be switched by an external magnetic field, a magnetic transistor could be made, with on and off configurations depending on the orientation of the middle magnetized layer.

Magnetic (spin) transistors are good candidates for logic devices (spin-logic).

Keywords: spintronics, magnetoelectronics, spin electronics, spin-based electronics, giant magnetoresistance, spin valves, magnetic tunneling junctions, tunneling magnetoresistance, colossal magnetoresistance, spin torque, momentum transfer, spin injection, magnetic semiconductor, spin coherence, spin Hall effect, anomalous Hall effect, magnetic transistor, spin transistor, spin polarization, magnetization, magnetic moment, magnetism, magnetic materials, MRAM, magnetic random access memory, universal memory, DRAM, spin logic,