Spintronics: Combination of Nanotechnology & Superconductivity

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Abstract

Advances in fabrication & characterization of magnetic & superconductivity materials on nanometre length scales paves the way for new experimental, theoretical & technological frontiers. This paper emphasize on "spintronics": it is a nanoscale technology in which information is carried not by the electon's charge, as it is in conventional microchips, but by the electron's intrinsic spin, by controlling the spin degree of freedom in solid – state heterostructures & magnetic quantum dots, Spintronics offers new possibilities for developing data processing speeds, lower electric consumption & the ability to carry out radically new quantum computations over conventional electronics.

Spintronics a prototype device that is already in use in industry as a read head & a memory –storage cell is the giant – magneto resistive (GMR) sandwich structure which consists of alternating ferromagnetic & non-magnetic metal layers. Experimental work is reviewed with the emphasis on the fundamentals & application in which external electric & magnetic field will be used to control spin & charge dynamics to create new functionalities which are ineffective with conventional electronics.

Key Words: spintronics, superconductivity, giant – magneto resistive (GMR), magnetic field, heterostructures, conventional electronics etc.

INTRODUCTION

Spintronics emerged from discoveries in the 1980s concerning spin-dependent electron transport phenomena in solid-state devices. This includes the observation of spin-polarized electron injection from a ferromagnetic metal to a normal metal by Johnson and Silsbee (1985), and the discovery of giant magnetoresistance independently by Albert Fert et al. and Peter Grünberg et al. (1988) The origins of spintronics can be traced back even further to the ferromagnet/superconductor tunneling experiments pioneered by Meservey and Tedrow, and initial experiments on magnetic tunnel junctions by Julliere in the 1970s. 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.

In 2012, IBM scientists (international business machines computer laboratory) mapped the creation of persistent spin helices of synchronized electrons persisting for more than a nanosecond. This is a 30-fold increase from the previously observed results and is longer than the duration of a modern processor clock cycle, which opens new paths to investigate for using electron spins for information processing.

The spin of the electron is an angular momentum intrinsic to the electron that is separate from the angular momentum due to its orbital motion. The magnitude of the projection of the electron's spin along an arbitrary axis is $\frac{1}{2}\hbar$, implying that the electron acts as a Fermion by the spin-statistics theorem. Like orbital angular momentum, the spin has an associated magnetic moment, the magnitude of which is expressed as-

$$m = \frac{\sqrt{3}}{2}\frac{q}{m_e}\hbar \quad . \text{......................} \textbf{(1)}$$

In a solid the spins of many electrons can act together to affect the magnetic and electronic properties of a material, for example endowing a material with a permanent magnetic moment as in a ferromagnet.

In many materials, electron spins are equally present in both the up and the down state, and no transport properties are dependent on spin. A spintronic device requires generation or manipulation of a spin-polarized population of electrons, resulting in an excess of spin up or spin down electrons. The polarization of any spin dependent property X can be written as-

$$P_X = \frac{X_\uparrow - X_\downarrow}{X_\uparrow + X_\downarrow} . \text{......................} \textbf{(2)}$$

A net spin polarization can be achieved either through creating an equilibrium energy splitting between spin up and spin down such as putting a material in a large magnetic field (Zeeman effect) or the exchange energy present in a ferromagnet; or forcing the system out of equilibrium. The period of time that such a non-equilibrium population can be maintained is known as the spin lifetime, τ. In a diffusive conductor, a spin diffusion length λcan also be defined as the distance over which a non-equilibrium spin population can propagate. Spin lifetimes of conduction electrons in metals are relatively short (typically less than 1 nanosecond), and a great deal of research in the field is devoted to extending this lifetime to technologically relevant timescales.

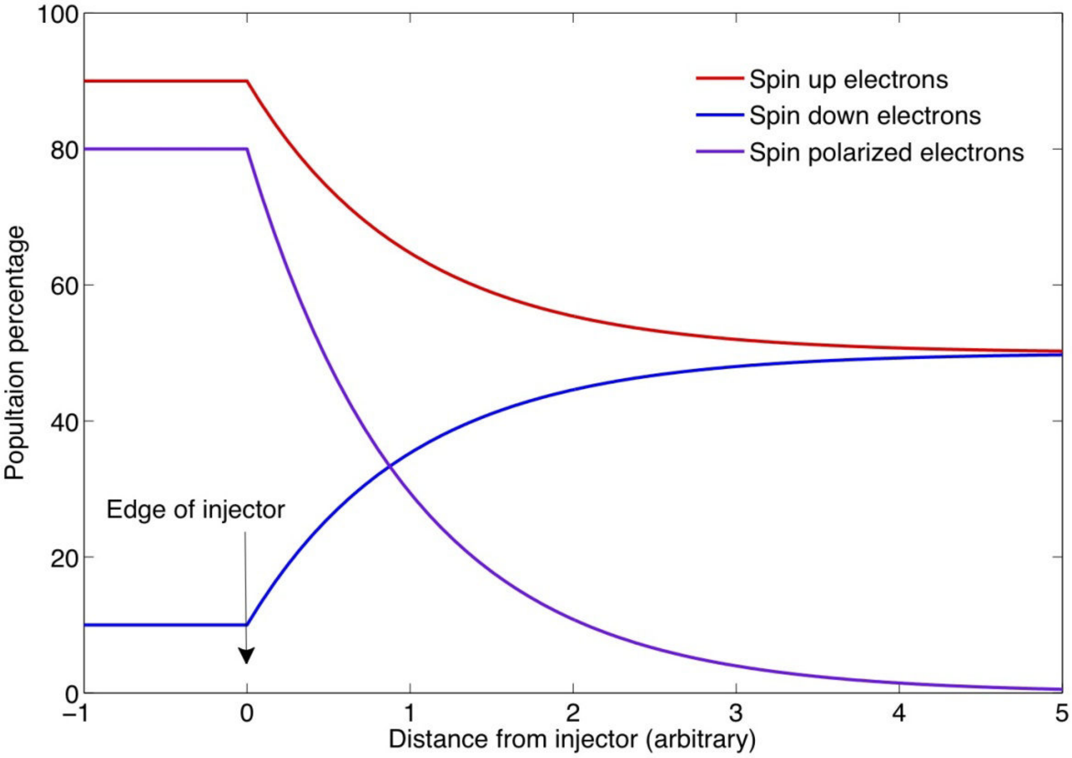

Fig-(1) plot showing a spin up, spin down, and the resulting spin polarized population of electrons. Inside a spin injector, the polarization is constant, while outside the injector, the polarization decays exponentially to zero as the spin up and down populations go to equilibrium.

There are many mechanisms of decay for a spin polarized population, but they can be broadly classified as spin-flip scattering and spin dephasing. Spin-flip scattering is a process inside a solid that does not conserve spin, and can therefore send an incoming spin up state into an outgoing spin down state. Spin dephasing is the process wherein a population of electrons with a common spin state becomes less polarized over time due to different rates of electron spin precession. In confined structures, spin dephasing can be suppressed, leading to spin lifetimes of milliseconds in semiconductor quantum dots at low temperatures.

By studying new materials and decay mechanisms, researchers hope to improve the performance of practical devices as well as study more fundamental problems in condensed matter physics.

Metal-based spintronic devices

The simplest method of generating a spin-polarised current in a metal is to pass the current through a ferromagnetic material. The most common applications of this effect involve giant magnetoresistance (GMR) devices. A typical GMR device consists of at least two layers of ferromagnetic materials separated by a spacer layer. When the two magnetization vectors of the ferromagnetic layers are aligned, the electrical resistance will be lower (so a higher current flows at constant voltage) than if the ferromagnetic layers are anti-aligned. This constitutes a magnetic field sensor.

Two variants of GMR have been applied in devices: (1) current-in-plane (CIP), where the electric current flows parallel to the layers and (2) current-perpendicular-to-plane (CPP), where the electric current flows in a direction perpendicular to the layers.

Other metals-based spintronics devices:

- Tunnel magnetoresistance (TMR), where CPP transport is achieved by using quantum-mechanical tunneling of electrons through a thin insulator separating ferromagnetic layers.
- Spin-transfer torque, where a current of spin-polarized electrons is used to control the magnetization direction of ferromagnetic electrodes in the device.
- Spin-wave logic devices utilize the phase to carry information. Interference and spin-wave scattering are utilized to perform logic operations.

Spintronic-logic devices

Non-volatile spin-logic devices to enable scaling beyond the year 2025 are being extensively studied. Spin-transfer torque-based logic devices that use spins and magnets for information processing have been proposed and are being extensively studied at Intel. These devices are now part of the ITRS exploratory road map and have potential for inclusion in future computers. Logic-in memory applications are already in the development stage at Crocus and NEC.

Read heads of modern hard drives are based on the GMR or TMR effect.

Motorola has developed a first-generation 256 kb magnetoresistive random-access memory (MRAM) based on a single magnetic tunnel junction and a single transistor and which has a read/write cycle of under 50 nanoseconds. (Everspin, Motorola's spin-off, has since developed a 4 Mb version. There are two second-generation MRAM techniques currently in development: thermal-assisted switching (TAS) which is being developed by Crocus Technology, and spin-transfer torque (STT) on which Crocus, Hynix, IBM, and several other companies are working.

Another design in development, called racetrack memory, encodes information in the direction of magnetization between domain walls of a ferromagnetic metal wire.There are magnetic sensors using the GMR effect.

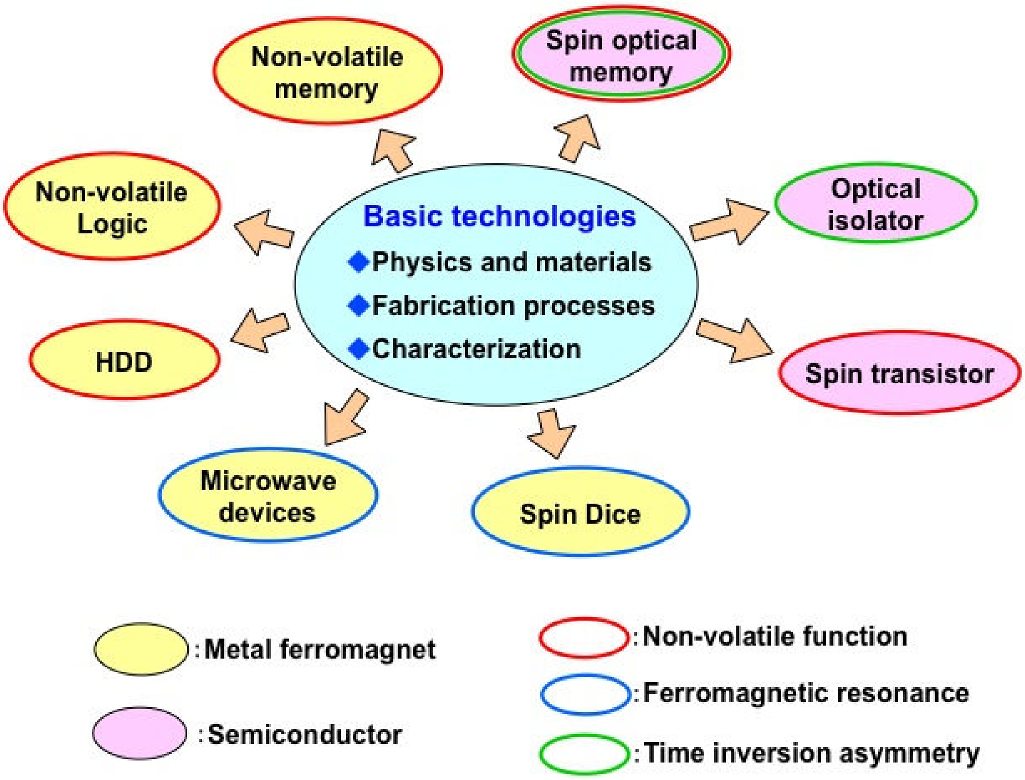

Fig.-(2) Applications of spintronics

Semiconductor-based spintronic devices

Ferromagnetic semiconductor sources (like manganese-doped gallium arsenide GaMnAs), increase the interface resistance with a tunnel barrier, or using hot-electron injection.

Spin detection in semiconductors is another challenge, met with the following techniques:

- Faraday/Kerr rotation of transmitted/reflected photons
- Circular polarization analysis of electroluminescence
- Nonlocal spin valve (adapted from Johnson and Silsbee's work with metals)
- Ballistic spin filtering

The latter technique was used to overcome the lack of spin-orbit interaction and materials issues to achieve spin transport in silicon, the most important semiconductor for electronics.

Because external magnetic fields (and stray fields from magnetic contacts) can cause large Hall effects and magnetoresistance in semiconductors (which mimic spin-valve effects), the only conclusive evidence of spin transport in semiconductors is demonstration of spin precession and dephasing in a magnetic field non-collinear to the injected spin orientation. This is called the Hanle effect.

Applications using spin-polarized electrical injection have shown threshold current reduction and controllable circularly polarized coherent light output. Examples include semiconductor lasers. Future applications may include a spin-based transistor having advantages over MOSFET devices such as steeper sub-threshold slope.

Magnetic-tunnel transistor

The magnetic-tunnel transistor with a single base layer, by van Dijken et al. and Jiang et al.,has the following terminals:

- Emitter (FM1): It injects spin-polarized hot electrons into the base.
- Base (FM2): Spin-dependent scattering takes place in the base. It also serves as a spin filter.
- Collector (GaAs): A Schottky barrier is formed at the interface. This collector regions only collects electrons when they have enough energy to overcome the Schottky barrier, and when there are states available in the semiconductor.

The magnetocurrent (MC) is given as-

$$MC = \frac{I_{c,p} - I_{c,ap}}{I_{c,ap}} \qquad \text{......................} \; \mathbf{(3)}$$

And the transfer ratio (TR) is

$$TR = \frac{I_C}{I_E} \qquad \text{......................} \; \mathbf{(4)}$$

MTT promises a highly spin-polarized electron source at room temperature.

Plastic Spintronics

Spintronics uses magnetic fields to control the spin of electrons. In the current issue of the Journal of Advanced Materials, Epstein and his coauthors report using a magnetic field to make nearly all the moving electrons inside a sample of plastic, spin in the same direction, an effect called spin polarization. Achieving spin polarization in plastic is the first step in converting this material into a read/re-writable memory storage medium.

The advent of plastic electronics opens up many opportunities for new technologies such as flexible displays and inexpensive solar cells. Plastic Spintronics devices would weigh less than traditional electronics devices and cost less to manufacture. Using plastic may solve another problem currently faced by developers: spinning electrons must be able to move smoothly between components made of different materials. But transition from one material to another can sometimes alter the spin of an electron and hence the data stored in that electron's spin would be lost.

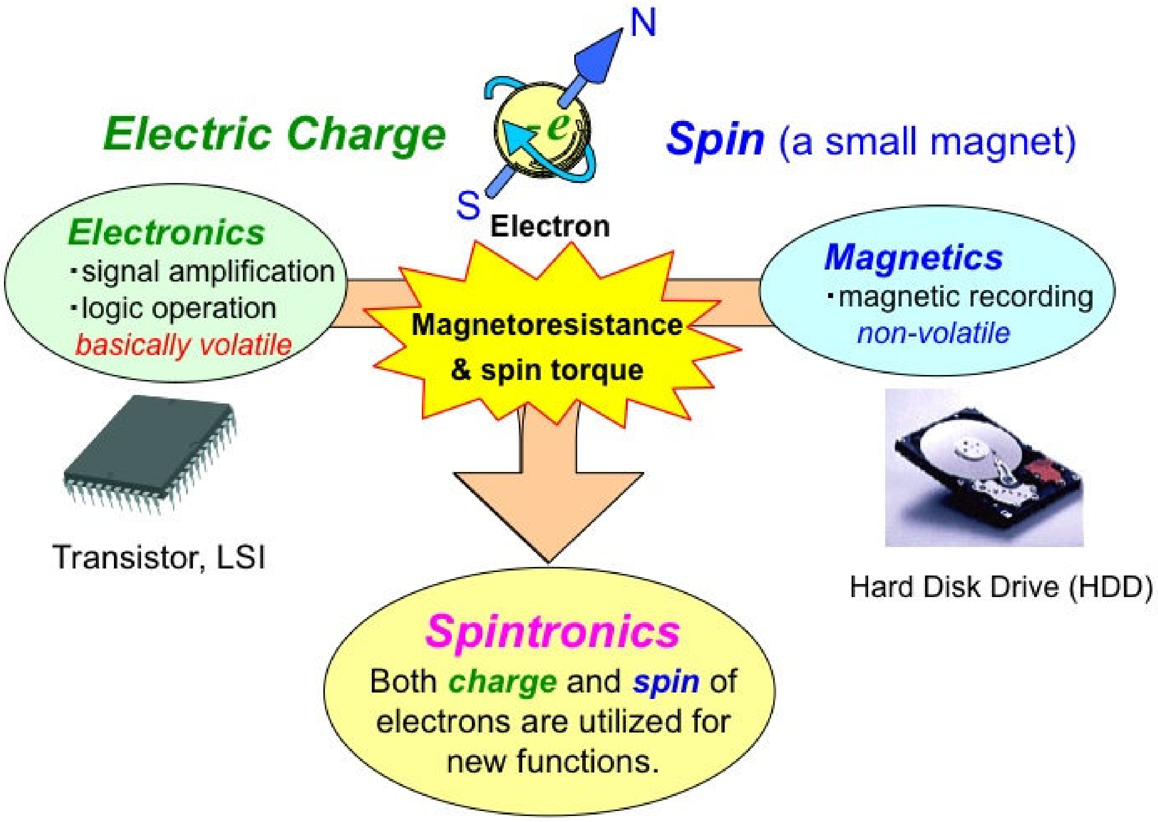

Fig - (3) Read and Write Operations using Spintronics

Conclusion

Spintronics is a technology with a fast track from the discovery of GMR and MTJ materials to the incorporation of these materials in commercial devices. Spintronics read heads dominate the hard-disk market. Magnetic sensors based on spintronics are making inroads in markets where some combination of high resolution, high sensitivity, small size, and low power are required. Digital data couplers and displacing opto isolators in many applications and are making inroads into new markets heretofore unavailable. MRAM devices are on the horizon and offer the promise of laptop computers that do not need to boot up and cell phones with increased battery time and increased capabilities.

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