Utilization of Spintronics

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Abstract-Spintronics refers commonly to phenomena in which the spin of electrons in a solid state environment plays the determining role.In a narrow sense Spintronics refers to spin based electronicsi.e. spin-polarized transport in metals and semiconductors. The goal of this applied Spintronics is to find effective ways of controlling electronic properties, such as the current or accumulated charge, by spin or magnetic field, as well as of controlling spin or magnetic properties by electric currents or gate voltages. The ultimate goal is to make practical device schemes that would enhance functionalities of the current charge based electronics.Spintronics devices are based on a spin control of electronics, or on an electrical and optical control of spin or magnetism. Most semiconductor device systems are still theoretical concepts, waiting for experimental demonstrations.

Index Terms-Giant Magnetoresistance, Magnetism, Magnetoresistance,Spintronics, Tunneling Magnetoresistance.

I. INTRODUCTION

In the information era, a new promising science has been strongly addressed called Spintronics, the contracted form of spin based electronics. The 2007 Nobel Prize for physics, with whom A. Fert and P. A. Grunberg have been awarded, is another clear signal that the importance of Spintronics for society is worldwide understood. In the far 1933 the physicist F. Mott published his innovative concept of spin dependent conduction. Only forty years later experimental evidence of current spin polarization was reported by P. Tedrow and R. Meservey, carrying out experiments of tunneling between ferromagnetic metals and superconductors. In 1975 experiments on a Fe/GeO/Co junction led to the discovery of tunneling magnetoresistance (TMR) by M. Julliere, only verified in 1995 by T. Miyazaki and N. Tezuka and J. S. Moodera. In1988 experiments on layered thin films of FMs alternated to a non-magnetic metal (NM) led to the simultaneous and independent discovery of the giant magnetoresistance (GMR) by A. Fert and P. A. Grunberg.Nowadays theprincipal application of Spintronics devices is the magnetic data storage with an information density growth rate faster than the corresponding Moore law.

In a narrow sense spintronics refers to spin electronics, the phenomena of spin-polarized transport in metals and semiconductors. In a broad sense spintronics is a study of spin phenomena in solids, in particular metals and semiconductors and semiconductor hetero-structures. Such studies characterize electrical, optical, and magnetic properties of solids due to the presence of equilibrium and non-equilibrium spin populations, as well as spin dynamics.An example is a spin field-effect transistor, which would change its logic state from ON to OFF by flipping the orientation of a magnetic field [1].

II. SILSBEE-JOHNSON SPIN-CHARGE COUPLING FOR SPIN DETECTION

In electrical spin injection we drive spin-polarized electronsfrom a ferromagnet into a nonmagnetic conductor. As aresult, non-equilibrium spin accumulates in the nonmagneticconductor. The opposite is also true: If a spin accumulation is generated in a nonmagnetic conductor that is in proximity of a ferromagnet, a current flows in a closed circuit, or an electromotive force (emf) appears in an open circuit. This inverse effect is called the Silsbee-Johnson spin-charge coupling. This coupling was first proposed by Silsbee (1980) and experimentally demonstrated by Johnson and Silsbee (1985) in the first electrical spin injection experiment.

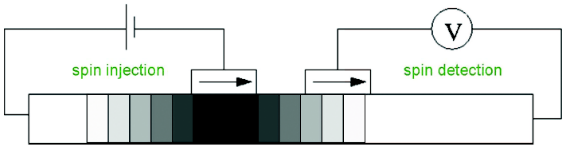

Figure 1: The Johnson-Silsbee non-local spin injection and detection scheme.

Physical system is shown in Fig. 1. Spin is injected bythe left ferromagnetic electrode, and detected by the rightone,making it a non-local measurement. The injected spindiffuses in all directions (here left and right), unlike forthe charge current. The non-equilibrium spin at the rightferromagnetic electrode is picked-up by the Silsbee Johnson spin-charge coupling, producing a measurable emf in the right circuit. Consider an F/N junction with a special boundary condition: a non-equilibrium spin is maintained, by whatever means, at the far right boundary of the nonmagnetic conductor:

$$\mu_{sN}(\infty) \neq 0. \quad (1)$$

At the far left boundary of the ferromagnetic region, the spin is assumed to be in equilibrium:

$$\mu_{sF}(-\infty) = 0. \tag{2}$$

Induced electromotive force, defined by,

$$emf = \mu_{sN}(\infty) - \mu_{sF}(-\infty). \tag{3}$$

The emf can be detected as a voltage drop. The drop of thequasi-chemical potential across the contact is due to the spinfiltering effect of the contact. If the contact conductance were spin-independent, the chemical potential would be continuous.The electrostatic potential drop across the contact is due tothe spin polarization of the ferromagnet as well as due tothe spin filtering effects of the contact. There is an emf developed if equilibriumspins in electrical contact with a nonequilibrium spin. This effect allows detection of non-equilibrium spin,by putting a ferromagnetic electrode over the region of spin accumulation. By measuring the emf across this junction, we obtain information about the spin in the nonmagnetic conductor.

III. SPINTRONICS DEVICES

In a narrow sense, spintronics refers to spin control of electronics. Say, flip a spin or turn on magnetic field and the current stops flowing, ideally. Similarly, we would like a device which would orient spin by passing a current or applying a gate voltage. In thisway the spin would be fully integrated withelectronics and we could write, store and manipulate, as well as read the information based on spin.

The goal is to make useful electronic devices that would enhance functionalities of the existing semiconductor technology. Thus far this goal has been elusive, although the field has gone through immense progress keeping us optimistic about its potential. The case at hand is metal spintronics, which has already revolutionized computer industrywith a device based on giant magnetoresistance.

A. GMR

The discovery of the giant magnetoresistance effect allowed increasing the density of the information stored in hard disks, leading to more than a hundredfold increase in their capacity. The idea is to increase the sensitivity of the electrical current due to magnetization changes. The GMR effect occurs in ferromagnetic layered nanostructures. Two ferromagnetic layers sandwich over a nonmagnetic conductor. If the magnetizations of the two layers are parallel, the resistance is small, if they are antiparallel, the resistance is large. The relative change of the resistance is called giant magnetoresistance. At room temperature the changes are typically about 10-50%, with the upper values obtained in multilayer systems (Grunberg, 2001). Why is the resistance different for the differentrelative orientations of magnetization? Take parallel magnetizations. The spacer layer between the ferromagnets is a few nanometers thick. Electrons injected there from one layer keep their spin orientation and can relatively easily continue to the second ferromagnetic layer. If the magnetizations are antiparallel, the injected electrons will be morelikely reflected from the second interface, due to the reduced density of states for that spin in the second ferromagnet. This interface scattering increases the resistance of the anti-parallel orientation[8].

B. MRAM

The physics is similar in description to GMR, although the transport is by tunneling through a nonmagnetic insulating layer, not ballistic transport through a metallic nano-region. A metallic TMR is being employed as a non-volatile magnetic random access memory (MRAM), whose operating principle is shown in Fig. 2. Non-volatility is crucial here: the information about a memory element is stored in the magnetization configuration of the ferromagnetic layers; this information need not be refreshed, nor does it disappear after the power is switched off.

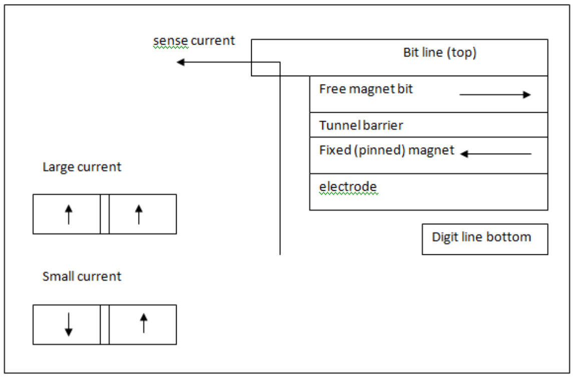

Figure 2: Magnetic Random Access Memory (MRAM).

C. Spin Transistor

The most sought for semiconductor Spintronics device is spin transistor. Since there are many spin transistors proposed, and only few convincingly demonstrated, it is too early to say in which direction the field develops[9]. Various designs have various advantages and disadvantages, but without experimental demonstrations theoretical proposals are hard to judge. We should also mention that the word transistor is often liberally used to describe any three terminal devices, without a prospect for current amplification. Such devices canbe useful for electrical injection or as spin valves, but not for logic elements which require voltage controlled ON and OFF states with the ratio of the electrical currents in these states of at least 1000 to 1. Selected spin transistor schemes are shown in Fig. 3.

The most straightforward scheme is a spin metal-oxide-silicon field-effect transistor (spin MOSFET). This device would act as a spin valve in the setting of a conventional field-effect transistor. If the magnetizations of the ferromagnetic source and drain (also called emitter and collector) are parallel, the transport channel is open (ON); if the magnetizations are antiparallel, the channel is closed (OFF). This structure is yet to be demonstrated.

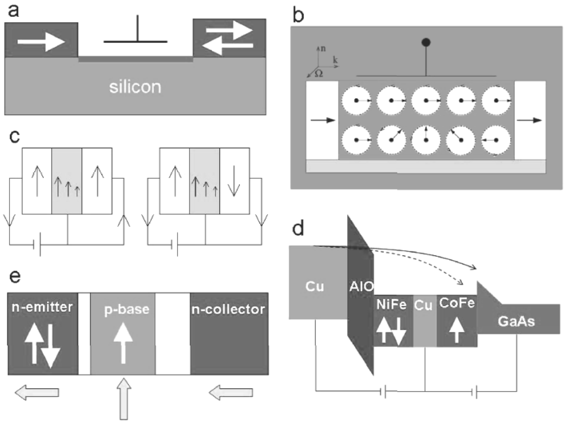

Figure 3: (a) spin metal-oxide-silicon field effect transistor (spin MOSFET), (b) Datta-Das spin FET, (c) Johnsons spin-valve transistor, (d) a hot electron spin-valve transistor, (e) magnetic bipolar junction transistor.

The so-called Datta-Das spin transistor, in Fig. 3(b), uses spin-orbit coupling of the Bychkov-Rashba type for its operational principle. The source and drain are ferromagnetic. The transport channel is a two dimensional electron gas. The top gate, which in conventionalfield-effect transistors controls the channel conductance, now controls the spin-orbit coupling strength. Electrons injected with momentum parallel to the transport feel an effective magnetic spin-orbit field transverse to that direction. The electron spins then process with a single precession frequency, assuming a ballistic one dimensional transport. Depending on the precession speed, the spin either processes very little (or even multiples of π), in which case the electron will enter into the drain (ON), or by π(or its odd multiples), in which case the electron bounces back, increasing the channels resistance (OFF). Different variants of the Datta-Das scheme have been proposed.

The Johnson spin switch, shown in Fig. 3(c), originally proposed as an all-metal Ohmic transistor is based on a spin-valve geometry in which the nonmagnetic layer offers an additional contact. This structure offers little amplification, if any, since the base current would be similar in magnitude to the collector current. The transistor works as follows: if the magnetizations of the two ferromagnetic layers are parallel, the collector current flows in the same direction as indicated, into the collector. If the magnetizations are antiparallel, the collector current is opposite.

Hot electron spin transistors form a large class of devices. These are usually hybrid metal/semiconductor structures, offering again little potential for currentamplification due to the large base current. Nevertheless, these devices offer huge magnetocurrents, as well as practical ways to inject spin into semiconductors such as silicon. In the structure shown in Fig. 3(d), the emitter is a nonmagnetic metal (Cu), while the collector is a nonmagnetic semiconductor (GaAs). The base is formed by a ferromagnetic spin-valve: NiFe/Cu/CoFe. The base forms a Schottky barrier with the collector. Electrons that tunnel from the emitter to the base are hot electrons (not thermalized to the Fermi level of the base). These electrons lose energy depending on the relative orientation of the magnetizations in the spin valve. If the magnetizations are parallel, the energy lossis greater than for an antiparallel orientation. The loss of energy is directly reflected in the collector current, since only the electrons of energy high enough to overcome the potential Schottky barrier contribute to the collector current. This large spin filtering effect has been demonstrated to give large magnetocurrent.

An all-semiconductor version of a hot electron spin transistor has also been proposed.

D. Magnetic Bipolar Transistor

Finally, the magnetic bipolar transistor, depicted in Fig. 3(e), is based on the conventional junction transistor design, substituting ferromagnetic semiconductors in the active regions, say the base. This transistor allows for spin-control of current amplification due to spin-dependent tunneling across the emitter/base contact (called the depletionlayer). Although the diode version of the transistor (a single magnetic p-n junction) has been demonstrated, the transistor is still a theoretical concept.

E. Spintronics in Other Fields

Other spintronics devices include a proposed scheme for reconfigurable logic, a room temperature spin-transference device, electron spin resonance transistor, 2D channel spin valve controlledby ferromagnetic gates, spin capacitor, spin lasers. Since at the moment most devices are theoretical concepts, it is simply too early to say which schemes will be practical, as well as which role and which functionalities will be played and taken over by spintronics devices from the future semiconductor technologies. Some of the spintronics devices are listed below,

1. Resonant tunneling diodes
2. Magnetic RTDs
    a) Paramagnetic spin-RTDs
    b) Ferromagnetic spin-RTDs
    c) Spin-RTDs with magnetic barriers
    d) Magnetic inter-band RTDs
    e) Nonmagnetic spin-RTDs
3. Digital magneto resistance in magnetic MOBILEs
4. Magnetic diode
5. Magneto-amplification

IV. ADVANTAGES AND DISADVANTAGES

Sensors, switches and isolators can be made from Spintronics technology. The cost and power are extremely low, making these devices highly competitive. The performance of the isolators in particular, can bemuch better than their optical counterparts at lower cost. Memories built from these devices could ultimately compete with mainstream semiconductor memories in density, speed, and cost, with the important added bonus of non-volatility and the potential for significant tolerance to extremely harsh environments. 16 Kbit nonvolatile, radiation hard, magnetic random access memory chip (under a square inch in size and had an access time of under 100 nanoseconds) was developed by Honeywell using their radiation hard CMOS under-layers.They are simultaneously developing a magnetic memory chip based on anisotropic magnetoresistance (AMR).

GMR memory was at least a factor of four faster based on the larger changes in resistance that GMR afforded[10].This memory has unlimited read and write. This is better than ferroelectric-RAM (FeRAM) which still is limited in the number of times it can be cycled. The memory has a nondestructive read out (NDRO) so that the information will not be lost and the data storage has very high integrity[11].

Advantages:

1. Non-volatility,
2. Increased data processing speed
3. Decreased electric power consumption
4. Increased integration densities
5. Nondestructive read out (NDRO)

Disadvantages

1 Hard to achieve complete spin polarization
2 Very difficult to maintain spin polarization for long time at room temperature
3 Electron spin get distorted due to solid impurities and optical source
4 Room temperature demonstration of all these spin devices is quite difficult

V. CONCLUSION

The new field of Spintronics was born in the intersection of magnetism, electronic transport, and optics. It has achieved commercial success in some areas and is advancing toward additional applications that rely on recent fundamental discoveries. The field is sufficiently broad that there is no single central obstacle to the application of these fundamental physical principles to new devices. Some of the advances that might bemost helpful would be room-temperature demonstrations ofinjection of nearly 100% spin-polarized current from a ferromagnetic metal, ferromagnetic semiconductor with very low optical loss.

These are, of course, only a small selection of the possible areas that would have a tremendous effect on Spintronics research and on achieving the devices described here (and others).

REFERENCES

[1] A. Chiolerio, *Spintronic Devices*. Phd thesis, POLITECHNIC OF TURIN, February 2009.

[2] E. C. Stoner, "Collective electron ferromagnetism," *American Scientist*, vol. 938, pp. 339-371, 1931.

[3] A. M.-A. Jaroslav Fabian, "Semiconductor spintronics," Department of Physics, State University of New York at Buffalo, Buffalo NY, 14260, USA, 2003.

[4] M. Johnson and R. H. Silsbee, "Spin-injection experiment,"*Phys. Rev.B, Condens.Matter*, vol. 37, no. 10, pp. 5326-5335, 1988.

[5] M. E. Flatte, "Spintronics," *IEEE TRANSACTIONS ON MAGNETICS*, vol. 54, pp. 907-920, May 2007.

[6] R. Duine, "Spintronics,"Leuvenlaan 4, 3584 CE Utrecht, Netherlands, February 2010.

[7] M. Bibes and A. Barthelemy, "Oxide Spintronics," *IEEE TRANSACTIONS ONMAGNETICS*, vol. 54, pp. 1003-1023, May 2007.

[8] P. G. A. Fuss, R. E. Camley, "Novel magnetoresistance effect in layered magnetic structures: Theory and experiment,"*Phys. Rev. B, Condens. Matter*, vol. 42,pp. 8110-8120, November 1990.

[9] S. D. Sarma, "Spintronics: A new class of device based on the quantum of electronspin,"*American Scientist*, vol. 89, pp. 516-523, December 2001.

[10] S. A. Wolf and D. Treger, "Spintronics: A new paradigm for electronics for the newmillennium," *IEEE TRANSACTIONS ON MAGNETICS*, vol. 36, pp. 2748-{2751, September 2000.

[11] J. L. Stuart A. Wolf, "The promise of nanomagnetics and Spintronics for future logicand universal memory,"*Proceedings of the IEEE*, vol. 98, pp. 2155-2168, December 2010.

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