Overview 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. Spintronics devices are based on a spin control of electronics, or on an electrical and optical control of spin or magnetism. This review provides a new promising science which has been strongly addressed as Spintronics, the contracted form of spin based electronics and presents selected themes of semiconductor Spintronics, introducing important concepts in spin transport, spin injection, Silsbee-Johnson spin-charge coupling, and spin dependent tunneling. Most semiconductor device systems are still theoretical concepts, waiting for experimental demonstrations.

Keywords- Giant Magnetoresistance, Magnetism, Magnetoresistance, Spintronics, Tunneling Magnetoresistance.

1. Introduction

In a narrow sense Spintronics refers to spin electronics, the phenomena of spin-polarized transport in metals and semiconductors. The goal of this applied Spintronicsis 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. 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]. 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.

1.1 History

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 polarisation 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.

2. Spin Injection

2.1 Spin Drift

Electrons which can be labeled as spin up and spin down. The total number of electrons is assumed to be preserved. If the electron densities are $n\uparrow$and $n\downarrow$for the spin up and spin down states, the total particle density is,

$$n = n\downarrow + n\downarrow . \qquad (1)$$

while the spin density is,

$$s = n\downarrow - n\downarrow. \tag{2}$$

Let probability of *w* thata spin is flipped in the time of τ, so that the spin flip rate is *w/* τ. We will assume that *w* <<1.The actual spin flip probability during therelaxation time τis typically 10^{-3} to 10^{-6}; so that electrons need to experience thousandsscatterings before spin flips. Therefore the density spin polarization as well as the current spin polarization is given by,

$$P_n = \frac{n_\uparrow - n_\downarrow}{n} = \frac{s}{n}, \tag{3}$$

$$P_j = \frac{j_\uparrow - j_\downarrow}{nj} = \frac{j_s}{j}. \tag{4}$$

this will be useful in our model of spin injection.

2.2 Spin Injection Standard Model

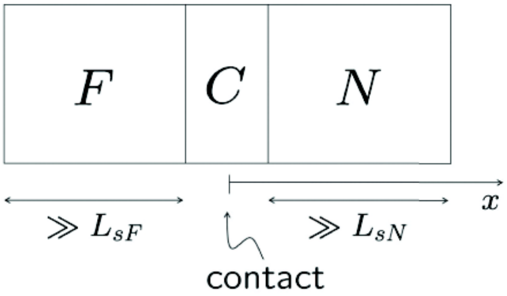

Figure 1: Scheme of our spin-injection geometry.

The standard model of spin injection has its roots in the original proposal of Aronov (1976). The thermodynamics of spin injection has been developed by Johnson and Silsbee, who also formulated a Boltzmann-like transport model for spin transport across ferromagnet nonmagnet (F/N) interfaces. Our goal is to find the current spin polarization, $P_j(0)$ in the normal conductor. We will assume that the lengths of the ferromagnet and the nonmagnetic regions are greater than the corresponding spin diffusion lengths. The spin injection scheme is illustrated in Fig. 1. The ferromagnetic conductor (F) forms a junction with the nonmagnetic conductor (N). The contact region (C) is assumed to be infinitely narrow, forming the discontinuity at $x = 0$. It is assumed that the physical widths of the conductors are greater than the corresponding spin diffusion lengths. We assume that at the far ends of the junction, the non-equilibrium spinvanishes. We now look at the three regions separately. The ferromagnet, contact, and normal conductor regions are identified. The electric current splits into the spin up and spin down components, each passing through the corresponding spin-resolved resistors[3].

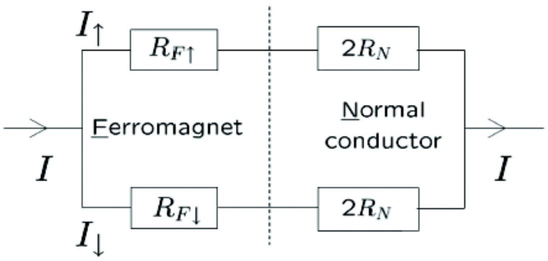

Figure 2: The equivalent circuit of the standard model of spin injection in F/N junctions.

i. Ferromagnet

Current spin polarization at x = 0 in the ferromagnet is,

$$p_{jF}(0) = p_{\sigma F} + 4\frac{1}{j}\frac{\sigma_{f\uparrow}\sigma_{f\downarrow}}{\sigma_f}, \tag{5}$$

Where effective resistance of the ferromagnet,

$$R_F = \frac{\sigma_f}{4\sigma_{f\uparrow}\sigma_{f\downarrow}} L_{sF}. \tag{6}$$

This is not the electrical resistance of the region, only an effective resistance that appears in the spin-polarized transport and is roughly equal to the actual resistance of the region of size L_{sF}.

ii. Nonmagnetic Conductor

Since in the nonmagnetic conductor $P_\sigma = 0$, and $\sigma_{N\downarrow} = \sigma_{N\uparrow}$, the current spin polarization in the nonmagnetic conductor then becomes,

$$p_{jN}(0) = -\frac{1}{j}\frac{1}{\sigma_N}, \tag{7}$$

where, effective resistance of the nonmagnetic region,

$$R_F = \frac{L_{sF}}{\sigma_N}. \tag{8}$$

iii. Contact

The conductance spin polarization is,

$$P_\Sigma(0) = \frac{\Sigma_\uparrow - \Sigma_\downarrow}{\Sigma} \tag{9}$$

Where, $\Sigma = \Sigma_\uparrow + \Sigma_\downarrow$is the conductance, while spin conductance is$\Sigma = \Sigma_\uparrow - \Sigma_\downarrow$ and the effective resistance of the contact is,

$$R_c = \frac{\Sigma}{4\Sigma_\downarrow\Sigma_\uparrow}, \tag{10}$$

Current spin polarization, at the contact given by,

$$p_{jc}(0) = P_\Sigma + \frac{1}{j}\frac{4\Sigma_\downarrow\Sigma_\uparrow}{\Sigma}. \tag{11}$$

Let assume spin current continuity at the contact:

$$P_j = P_{jf} = P_{jn} = P_{jc}. \tag{12}$$

The above equalities are justified if spin-flip scattering can be neglected in the contact. For contacts with paramagnetic impurities, we would need to take into account contact spin relaxation which would lead to spin current discontinuity. This assumption of the low rate of spin flip scattering at the interface should also be carefully reconsidered when analyzing room temperature spin injection experiments. Using the spin current continuity equations, we can solve our algebraic system and readily obtain for the spin injectionefficiency,

$$p_j = \frac{R_F\, p_{\sigma F} + R_c P_{\Sigma}}{R_F + R_c + R_N}. \qquad (13)$$

The standard model of spin injection can be summarized by the equivalent electrical circuit shown in Fig. 2. Spin up and spin down electrons form parallel channels for electric current. Each region of the junction is characterized by its own effective resistance, determined by the spin diffusion lengths in the bulk regions, or by the spin-dependentconductance in the contact.

3. Spin Detection

3.1. Silsbee-Johnson Spin-charge Coupling

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.

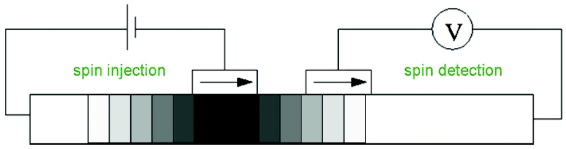

Figure 3: The Johnson-Silsbee non-local spin injection and detection scheme.

Physical system is shown in Fig. 3. 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:

$$\mu_{sN}(\infty) \neq 0. \qquad (14)$$

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

$$\mu_{sF}(-\infty) = 0. \qquad (15)$$

Induced electromotive force, defined by,

$$emf = \mu_{sN}(\infty) - \mu_{sF}(-\infty). \qquad (16)$$

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.

3.2. Giant Magneto Resistance (GMR)

GMR or the MR is the percent difference in resistance for parallel and antiparallel orientations of the two ferromagnetic regions in the spin valve. Spin valves are nanostructures that consist of stacked layers of magnetic and nonmagnetic material. They are built of two small Ferro-magnets (Co or an alloy of Ni and Fe called permalloy), separated by a nonmagnetic spacer layer (such as Cu) (Fig. 3). The typical thicknesses of the layers are in the order of 10 - 100 nm, and may be even smaller. A current can be applied to the spin valve in two directions:

a) CIP: Current In Plane/Parallel to the planes.
b) CPP: Current Perpendicular to planes.

(Separating magnetic and spacer layers)

3.2.1CIP

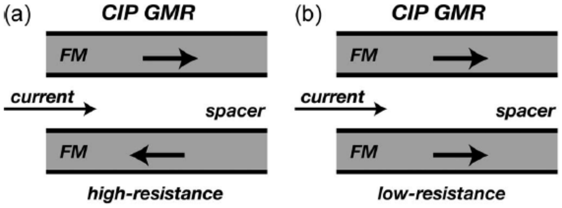

Figure 4: (a) High-resistance and (b) low-resistance geometry of CIP GMR.

The initial discovery of GMR was for a configuration(Fig. 4. for a spin valve) called ascurrent-in-plane GMR (CIP GMR). Shortly thereafter, asimpler experimental geometry was investigated (Fig. 5,current perpendicular-to-plane configuration). In each of these configurations, the two ferromagnetic regions are separated by a region of nonmagnetic metal, typically with a higher conductivity than either of the two ferromagneticlayers[5].

3.2.2CPP

In the experimental setup of CPP, one of theseferromagnetic layers is pinned, i.e., its direction ofmagnetization, denoted by Ω_1(Fig. 5), is fixed. Thisis in practice achieved by growing the magnetic layer on top of an anti-ferromagnet. The other magnetic layer of the spin valve, whose direction of magnetization is denoted by Ω_2, is called the free ferromagnet, and is not pinned and allowed to point in any direction. Usually however, the magnetic anisotropy energy is such that the low-energy configurations for the free ferromagnet are to point either parallel or antiparallel to the pinned ferromagnet[6].

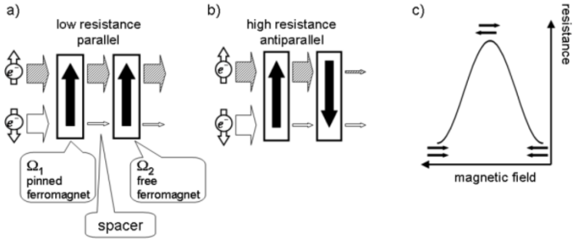

Figure 5: giant magnetoresistance in a spin valve.

An external magnetic field, below a certain magnitudecan change the magnetization direction of the free ferromagnet without altering the direction of magnetization of the pinned ferromagnet. This leads to the phenomenon of giant magnetoresistance (GMR). An experimental measurement of the resistance as a function of the magnetic field yields a curve like in Fig. 5(c). Consider the situation for thesmallest (negative) value of the magnetic field. In thisstrong-magnetic-field situation both the pinned and freemagnetic layer will be aligned with the external field and therefore be parallel. In this situation the resistance is small (RP = 0:3415 Ohm). As the field is decreased to cross zero towards small positive values the free ferromagnetic layer changes direction (in Fig. 5(b)) and the resistance changes to a large value (RAP = 0:3425 Ohm). At this point the pinned and free ferromagnets are pointing in opposite directions and are thus antiparallel.At even higher magnetic fields the pinned ferromagneticlayer also aligns with the external field and is hence again parallel to the free layer. In this situation the resistance is again small. We conclude that the resistance is related to the relativeconfiguration of the magnetic layers in the spin valve: an antiparallel configuration implies high resistance whereas a parallel configuration implies low resistance (Fig. 5(c)).

$$GMR = \frac{RAP - RP}{RAP}. \qquad (17)$$

Where*RP* and *RAP* correspond to the resistance measured in parallel and antiparallel configurations.

When GMR was first observed, ratiosof ~10% were reported. Since this change of resistanceis large the phenomenon was dubbed as giant. Spin valves are useful because they are very sensitive to changes in an external magnetic field. Moreover, a change in a magnetic field results in a change of resistance and is therefore easily observed. In all hard-disk drives build after the late 1990's the read heads make use of a spin valve.

3. 3 Tunneling Magnetoresistance (TMR)

In 1975 Julliere reported the first results concerningan experiment performed on a Fe/Ge/Co junction, i.e., ajunction made of a semiconducting slab, sandwiched between two ferromagnetic leads. The experiment showed a dependence of the resistance on whether the mean magnetizations of the two ferromagnetic films were oriented in a parallel or antiparallel configuration.Although in both cases the electrons tunnel through the same Ge semiconducting barrier, leading to a high resistance, the measured resistance was higher in the case of the antiparallel alignment. This phenomenon, in which the resistance of a magnetic tunnel junction (MTJ) depends on the relative orientation of the magnetization in the ferromagnetic leads,was termed the tunneling magnetoresistance (TMR) effect. The size of the tunneling magnetoresistance is characterized by the quantity,

$$TMR = \frac{\mathrm{RAP} + \mathrm{RP}}{\mathrm{RP}} = \frac{GP - GAP}{GAP}. \qquad (18)$$

Where*RP* (*GP)* and *RAP* (*GAP)* correspond to the resistance (conductance) measured in parallel [see Figs. 6 a c] and antiparallel [see Figs. 6 b d] configurations, respectively. The TMR observed by Julliere in Fe/Ge/Co junctions was about 14% but it was only observable at liquid 'He' temperatures (and never reproduced).

The first reproducible TMR was demonstrated by Maekawa and Gafvert (1982) who observed a strong correlation between the tunnel conductance and the magnetization process in Ni/NiO/ferromagnets junctions with Ni, Fe, or Co as the counter electrode. The measured values of the TMR were, however, still very small at room temperature. It was not until 1995 that triggered by the success of the giant magnetoresistance(GMR) and with the advent of superior fabricationtechniques, ferromagnet/ insulator/ferromagnet structures were revisited and a large room-temperature TMR (~18%) was observed[7].

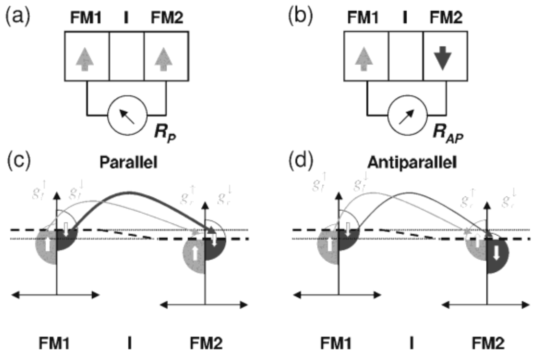

Figure 6: parallel (a,c) and anti-parallel (b,d) configurations for a tunnel junction .

Furthermore, the TMR effect can be employed as widely as the GMR effect e.g., highly sensitive magnetic-field sensors, magnetic read heads, spin-valve transistors, etc but with the advantage of providing higher magnetoresistive signal amplitudes. The most important, presently discussed application of the TMR effect is, however, in the realization of magnetic random-access memories (MRAM). The basic idea is tocombine the non-volatility of magnetic data storage with the short access times of present day random-access memories (DRAM). Thus, the recharging of the capacitors required for the periodic refreshing of the information in a DRAM is not needed in a MRAM device. Magnetic random-access memories are already commercially available.

4. 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. This project had as its goal the exploration of the utility of GMR devices for various sensor and memory applications. 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]. One of the reasons for the significant interest in this memory is the very favorable comparison of the potential performance of this memory to other nonvolatile memories like FLASH but also the favorable comparison to mainstream volatile memories like DRAM and SRAM. The 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]. It is intrinsically radiation hard and is limited only by the radiation hardness of the silicon circuits which control it.

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

5. 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).

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