Micromagnetic analysis and development of high sensitivity spin-valve magnetic sensors

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Abstract. In this paper we present a micromagnetic analysis and development of low-field magnetic sensors based on the planar Hall effect (PHE) in Permalloy (Ni\(_{80}\)Fe\(_{20}\)) thin films and spin-valve structures. We used these sensors for field measurements, biomolecules detection in lab-on-a-chip applications and angle positioning devices. Both field and angular PHE measurements were performed. Some distortions and hysteretic effects were observed at low magnetic fields for the angular dependence of the PHE voltage. Micromagnetic simulations were performed to explain the field and the angular dependence of the PHE voltage. We used dc biasing fields to improve the response of the PHE sensor and we compare these results with our micromagnetic simulations.

1. Introduction

Magnetoresistance effect (MR) which can be found in ferromagnetic (Fe, Co, Ni or alloys like Permalloy) based thin films is an attractive solution for the fabrication of magnetic sensors. The resistance behaviour of such thin films (3\(_d\) ferromagnetic alloys) is anisotropic with respect to the applied field direction, the MR being positive when the magnetic field is parallel to the current (longitudinal) and negative when the magnetic field is perpendicular to the current direction (transversal). This is the anisotropic magnetoresistance effect (AMR) and it was discovered in 1857 by William Thomson (Lord Kelvin). The AMR effect arises from anisotropic scattering due to spin orbit-orbit interaction. It is worth to mention that the MR effect in ferromagnetic thin films is determined by the sample magnetization rather than the external magnetic field, \(H\). The resistance produced by scattering reaches a maximum value when the magnetization direction is parallel or antiparallel (i.e. 0° or 180°) to the current direction and minimum when the magnetization is perpendicular to the current.

The magnetoresistance ratio \(\Delta R_{\text{AMR}}/R_0\) is relatively large for ternary Fe-Co-Ni alloys containing 70 to 90 atomic percent of Ni, amounting to at most 2.5 to 3% in 30 nm Permalloy (Ni\(_{81}\)Fe\(_{19}\)) films [1]. This is because when the film thickness becomes comparable or smaller than the mean free path of the carriers we should take in account the scattering processes at the surfaces and interfaces which lower the amplitude of the MR effects. Here, \(\Delta R_{\text{AMR}}=R_P-R_I\) is the amplitude of the AMR effect calculated in the saturated state when the applied magnetic field is parallel and perpendicular to the current respectively. Usually, \(R_0\) is the resistance in the saturated state when \(H\) is applied perpendicular to the current direction but in the film plane. For many applications in read heads and other sensors, Permalloy (Py) is the preferred choice due to its favourable soft magnetic properties. In the ternary Fe-Co-Ni diagram the Permalloy composition lies close to both to zero magnetostriiction and the zero
crystalline anisotropy line. Therefore, the magnetic behaviour of the prepared Permalloy films is dominated by the uniaxial in-plane anisotropy induced by a field applied during deposition. Thus, for a field along the hard axis, i.e. perpendicular to the anisotropy direction, the change of the magnetisation will result from a coherent magnetization rotation process. The maximum sensitivity and linearity is achieved when the magnetization is at 45° with respect to the current direction. The 45° alignment is commonly achieved using the Barber pole biasing technique, i.e. by patterning diagonal stripes of highly conductive metal (gold) onto the more resistive AMR material, as shown in figure 1(a). The current will then run perpendicular to these “barber pole” stripes while the magnetization vector remains preferentially along the long direction of the MR device. The application of an external magnetic field will rotate the magnetization with a resulting change in resistance as shown in figure 1(b).

Figure 1. (a) Barber-pole structure of conductive shunts that constrain the current to run at 45° to the rest position for the magnetization. (b) Resistance versus field for a properly biased AMR device.

To develop practical applications, such as contactless potentiometer or magnetic field sensors, it must to minimize the thermal drift and to optimize the MR response. For this purpose it is convenient to operate the device with the two or four active arms of a Wheatstone bridge. Each arm corresponds to one MR element. We have to mention that many other materials can be used for this application. Granular manganese perovskites, having ferromagnetic transitions above room temperature, are good candidates for use as magnetoresistive sensors [2]. Using thick films of $\text{La}_{2/3}\text{Sr}_{1/3}\text{MnO}_3$ prepared by screen printing on polycrystalline $\text{Al}_2\text{O}_3$ it can be developed a room temperature AMR sensor to build a contactless potentiometer.

Because of the AMR effect will appear an electric field perpendicular to the applied current, in a Hall effect geometry, even when the magnetic field is in the film plane [3, 4]. This is the so-called planar Hall effect (PHE). Using this setup we get direct access to the anisotropic part of the resistance with the advantage of a reduced thermal drift of the output signal.

In a single domain approximation, the PHE voltage is determined by $U_{\text{PHE}} = CM^2 j \sin 2\theta$, where $C$ is a constant determined by the structure properties, $j$ is the current density, $M$ is the saturation magnetization and $\theta$ is the angle between the current and the magnetization vector that, in turn, is determined by the value and direction of the external magnetic field [4, 5, 6].

Although the signal derived from the PHE is small, there is a higher signal-to-noise ratio (S/N) and a better thermal stability when compared to GMR spin valve sensors, hence it has the potential of detecting very small fields produced by various sources, single micro- or nanoparticles [7, 8]. The planar Hall voltage depends on the magnetization quadratically at the small applied fields and parabolically at the applied fields above the saturated magnetization. If the magnetization is initially oriented along the driving current inside the sensor, a rotation with angle $\theta$ produces a variation of the PHE voltage proportional with $\sin 2\theta$. This property can be used to build magnetic sensors. In order to obtain a coherent rotation of the magnetization inside the PHE sensor under the action of an applied magnetic field, a magnetic biasing can be used, as can be seen in the layout design presented in figure 2(a). This layout is also used to perform micromagnetic simulations regarding the field dependence of the PHE voltage. The micromagnetic simulations are using a method that minimises the free energy of the system in magnetic field based on the Stoner-Wohlfarth model [6, 9, 10].

Figure 2 (a) Micromagnetic simulation of the layout design in figure 2(a).
The current that is flowing through the conductive stripe generates a biasing magnetic field, $H_b$, which induces a single domain structure in sensor. The distance between the sensor’s surface and the conductive stripe is 200 nm. Applying a magnetic field, $H_{app}$, along a direction perpendicular on $H_b$, will produce a rotation of the magnetization and a voltage appears in a Hall effect setup, figure 2(a). Using micromagnetic simulations to find the rotation angle of the magnetisation, we can plot the field dependence of the PHE for different values of the biasing field, figure 2(b). From these very simple simulations it comes that the sensitivity and linearity of the field dependence of the PHE voltage can be tuned. In a single domain approximation, a lower biasing field gives a higher sensitivity but nonlinearity effects appear. On the other hand, the real magnetic films do not behave like single domain structures for low values of the biasing field. So, we expect to have a more complex field dependence of the measured PHE voltage accompanied, also, by some hysteretic effects.

2. Results and discussion

In what follows we will present some results obtained on Permalloy thin films and Permalloy based multilayered (ML) structures. The measurement system consists in a programmable current source Keithley 6221 and a nanovoltmeter 2182A. To generate and control the magnetic field we used a bipolar 4 quadrants BOP 10-100 MG power source that drives a 1.5 T electromagnet. The field is measured using a Lake Shore 475 DSP gaussmeter.

2.1. Field dependence of the PHE

Disk shape structures of Ni$_{80}$Fe$_{20}$ (15, 5 nm) and Co(30nm)/Cu(7 nm)/Ni$_{80}$Fe$_{20}$ (70 nm), 5 mm diameter, were deposited by magnetron sputtering onto oxidised Si substrate. No uniaxial anisotropy axes were defined during the samples deposition. Four Au contacts were deposited, symmetrically, by thermal evaporation to form the electrodes for the driving current and PHE signal, like in figure 2(a).

2.1.1. Si/SiO$_2$/Ni$_{80}$Fe$_{20}$(15.5 nm)

Because the sensor is a disk shape structure there is no shape anisotropy in the film plane and because there was no field applied during the deposition there is no uniaxial anisotropy.

In figure 3 we present the field dependence of the PHE effect measured when $\theta=45^\circ$ and no biasing, $H_b=0$. Because there are no anisotropy effects the magnetization process is mainly due to domain wall movement, i.e., the measured PHE voltage is a measure of the sample magnetization at square power. In this case, $\theta=45^\circ$, we get direct access to the anisotropic part of the resistance with the advantage of a reduced thermal drift of the output signal.
Figure 3. The field dependence of the PHE for a disk shape Permalloy film; the film is also shown.

This sensor can be used for field measurement by applying a biasing field, \( B_0 = 0.02 \) T, over this direction, \( \theta = 45^\circ \), using a small magnet, and an instrumentation circuit to compensate the offset and to amplify the signal, like in figure 4.

Figure 4. The biasing concept and the basic instrumentation schematic used to build a digital teslameter.

The field dependence, presented in figure 5, obtained after four scans between -0.02 to 0.02 T, reveals a very good linearity and a small hysteresis effect.

Figure 5. The field dependence of the measured voltage, \( U_{\text{meas}} \), using biasing and signal conditioning.
The setup presented in figure 4 represents the basic schematics of a digital gaussmeter which is using a thin film of Permalloy.

When the biasing setup presented in figure 2(a) is used, the magnetization keeps, in principle, the same value, but rotates under the action of the applied field. If the rotation angle is small, the variation of the PHE is proportional with $\theta$. Figure 6(a) presents the field dependence of the PHE voltage for different values of the biasing field, $H_b$. It is to be noted the hysteresis effects that appear even for a higher biasing field. For lower biasing fields, the magnetization do not saturates and the film will not behave like a single domain structure. So, when $H_b$ increases, the magnetization increases until $H_b$ reaches the saturation value. If during the film deposition a small field, 100 Oe, is applied in the film plane along two opposite contacts, a uniaxial anisotropy axis will be defined with about 5 Oe the amplitude of the anisotropy field. In this case, the hysteresis effects disappear, figure 6(b).

![Figure 6](image)

Figure 6. (a) the field dependence of the PHE voltage for a disk without uniaxial anisotropy and (b) the same dependence when there is a uniaxial anisotropy axis in the film plane over $\theta=0$.

To simulate the response of this structure, we considered a biasing setup like in figure 2(a) but instead of a square shape single domain structure, we used a disk shape structure, figure 7, divided in a mesh with magnetic single domains [6, 9, 10].

![Figure 7](image)

Figure 7. The structure (disc of Permalloy) used for micromagnetic simulations placed above the conductive stripe and (a) the magnetic moments orientations for $H_{appl}=0$ and (b) for $H_{appl}=100$ Oe.
Figure 7 illustrates this setup and presents the magnetic moments orientations for a biasing field of 50 Oe ($I_b=5.25$ mA) without an applied field, figure 7(a), and for an applied field of 100 Oe, figure 7(b). We see that the structure polarized at 50 Oe is not behaving like a single domain and explains the behaviour observed in figure 6. We performed this kind of micromagnetic simulations for three values of the biasing field and the results are presented in figure 8.

![Figure 7](image)

**Figure 7.** Disk shape structure Ni$_{80}$Fe$_{20}$ disk shape structure.

![Figure 8](image)

**Figure 8.** Micromagnetic simulations regarding the field dependences of magnetization (a) and planar Hall effect voltage (b) for different values of the biasing field.

From these simulations we see how the hysteresis width decreases when the biasing field increases and the magnetization reversal processes will be mainly due to rotation of the magnetization rather than domain wall displacements, figure 8(a). The amplitude of the calculated PHE voltage increases when $H_b$ increases and the saturation effect is obtained for high fields, figure 8(b). The calculated data for PHE signal presents a 180° phase shift and is not normalized to zero.

2.1.2. Si/SiO$_2$/Co(30 nm)/Cu(7 nm)/Ni$_{80}$Fe$_{20}$(70 nm)

In this subsection we present the same type of measurements and simulations made on a ML structure of the type Co/Cu/NiFe. In this case, the coupling effects between the magnetic layers through the nonmagnetic layer (Cu) and the higher anisotropy of the Co layer will play important roles on the magnetic field and angular behaviour of the PHE. Figure 9 presents the field dependences of the PHE voltage for $\theta=45^\circ$ without a biasing field and with a biasing field applied like in figure 2(a).

![Figure 9](image)

**Figure 9.** (a) Field dependences of the PHE voltage for a ML of Co/Cu/NiFe when (a) $\theta=45^\circ$ without a biasing field and (b) $\theta=0$ and a biasing field is applied; there is no uniaxial anisotropy.
Compared with the dependence presented for Si/SiO$_2$/Ni$_{80}$Fe$_{20}$ (15.5 nm) in subsection 2.1.1, we see in this case a higher coercive field of about 200 Oe (100 Oe for Ni$_{80}$Fe$_{20}$ 15.5 nm) and the influence of the Co layer which lowers the sensitivity at higher biasing fields. When the biasing field is higher, the Co layer tends to keep the orientation of the NiFe layer because of his anisotropy and the positive magnetostatic coupling between them. Again, when the biasing field is low there are hysteretic effects because of the reversal mechanism of magnetisation which is mainly due to domain wall movement.

To simulate the behaviour of this ML, we considered a design like in figure 7 which now consists in two magnetic layers separated by the nonmagnetic layer. The mesh structure and the interactions between the magnetic layers are described in [6, 9]. The orientations of the magnetic moments when the applied field is 100 Oe are presented in figure 10(a) for $H_b=50$ Oe and figure 10(b) for $H_b=200$ Oe.

![Figure 10. The magnetic moments orientations for $H_{appl}=100$ Oe when (a) $H_b=50$ Oe and (b) $H_b=200$ Oe; the red arrows (upper layer) denote the NiFe layer and blue arrows denote the Co layer.](image)

Figure 11 presents the field dependences of the magnetization and PHE voltage obtained by micromagnetic simulations for three values of the biasing field applied over $\theta=0$.

![Figure 11. Micromagnetic simulations regarding the field dependences of magnetization (a) and planar Hall effect voltage (b) for different values of the biasing field.](image)

From these simulations is revealed the influence of the Co layer; the ML do not saturates at 100 Oe and consequently the PHE do not saturates. The agreement between measured and simulated PHE characteristics is mainly a qualitative one and shows a decreasing of the PHE sensitivity when $H_b$ increases. Also, we can see from these simulations, a decreasing of the hysteresis width both for magnetization and PHE curves.
2.2. Angular dependence of the PHE

The equation that describes the PHE predicts a periodic dependence on the angle, $\theta$, between the current direction and the film magnetization. This dependence, in $\sin^2 \theta$, suggests another applications of the PHE: contactless potentiometer, magnetic compass, etc.

In figure 12 we present the angular dependences of the PHE voltage measured for the ML Si/SiO$_2$/Co(30 nm)/Cu(7 nm)/Ni$_{80}$Fe$_{20}$(70 nm) for different values of the applied field; there is no biasing field in this case. The applied magnetic field rotates with respect to the current direction [6].

![Figure 12](image)

**Figure 12.** Angular dependence of the PHE, measured for different values of the applied field.

These measurements show a very good agreement with the equation that predicts this behaviour. We see that the amplitude of the angular dependences depends on value of the applied field for lower values (100 and 200 Oe). This is because the magnetization needs a field higher than 200 Oe to saturate. If $H_{\text{appl}} > 500$ Oe the curves that describe the angular dependence of the PHE will have the same amplitude because the film magnetization saturates. These aspects are important for practical applications because the signal becomes field independent when $H_{\text{appl}}$ is higher than a critical value.

The micromagnetic simulations [6] performed on this structure in order to describe the angular dependence of the PHE are presented in figure 13.

![Figure 13](image)

**Figure 13.** Micromagnetic simulations of the angular dependence of the magnetization (a0 and (b) PHE voltage for different values of the applied rotating field; the arrows are guides for the eyes.
These simulations are in very good agreement with the experimental measurements and show how, at low fields, the magnetization cannot follow accurately the applied field. When \( H > 500 \) Oe, the angular dependence of the film magnetization shows a flat line which means that the magnetization has a constant value and follow the orientation of the rotating field. For this reason we observed distortions of these angular dependences at fields lower than 200 Oe [6].

3. Conclusions
In this paper we presented some measurements regarding the field and angular behaviour of the PHE in thin films and ML structures. We used disk shape samples in order to avoid the shape anisotropy in the film plane.

Micromagnetic simulations were used to explain some aspects observed in these measurements. Further works are necessary to improve the quality of the micromagnetic simulations.

Using samples with a small uniaxial anisotropy field the hysteresis effect can be lowered and by carefully adjusting the biasing field we can tune the sensor’s sensitivity. The same sensor can be used both for field and angular measurements.

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References
[1] Kools J C S, Coehoorn R, Folkerts W, De Nooijer M C and Somers G H K 1998 *Philips J. Research* **51** 125
[2] Balcells L, Calvao E, Fontcuberta J 2002 *J. Magn. Magn. Mater.* **242-245** 1166
[3] Prados C, Garcia D, Lesmes F, Freijo J J, and Hernando A 1995 *Appl. Phys. Lett.* **67** 718
[4] Montaigne F, Schuhl A, Nguyen Van Dau F, Encinas A 2000 *Sensors and Actuators* **81** 324
[5] Epshtein E M, Krikunov A I, Ogrin Yu F 2003 *J. Magn. Magn. Mater.* **258-259** 80
[6] Volmer M and Neamtu J 2008 *Physica B: Condensed Matter* **403** 350
[7] Chua K M, Adeyeye A O, Li Mo-Huang 2007 *J. Magn. Magn. Mater.* **310** e992
[8] Schuhl A, Nguyen Van Dau F, and Childress J R 1995 *Appl. Phys. Lett.* **66** 2751
[9] Volmer M and Neamtu J 2006 *Physica B: Condensed Matter* **372** 198
[10] Oti John O *SimulMag Version 2.0j, Micromagnetic Simulation Software, User’s Manual*, Electromagnetic Technology Division, National Institute of Standards and Technology Boulder, Colorado 80303.