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Development of a rotation sensor based on anisotropic magnetoresistance effect

M. VOLMER*, M. AVRAM[a], J. NEAMTU[b]
Physics Department, Transilvania University, 29 Eroilor, Brasov 500036, Romania
[a]*National Institute for Research and Development in Microtechnologies, Str. Erou Iancu Nicolae 32B, 72996 Bucharest, Romania*
[b]*Advanced Research Institute for Electrical Engineering, Splaiul Unirii 313, Bucharest, 030138, Romania*

We present here a method to increase the response quality of a rotation sensor based on the anisotropic magnetoresistance effect (AMR). The sensor is made by deposition of thin layers of $Ni_{80}Fe_{20}$ (Permalloy) or $Ni_{80}Fe_{20}$/NM/$Ni_{80}Fe_{20}$ structures. NM denotes Cu or Al_2O_3 layers. We used a circular shape deposition mask with approximately 5 mm in diameter. Using a Hall effect geometry we get direct access to the anisotropic part of the resistance with the advantage of a reduced thermal drift of the output signal. Because of the contacts misalignments and hysteresis effects in field dependence of the electrical resistance, the angular behaviour of the Planar Hall effect (PHE) voltage presents some distortions. Making PHE measurements for Permalloy and multilayers (ML) structures over two orthogonal directions for each angle, we obtained, by summating the results, a very symmetrical signal with two periods for a complete rotation in magnetic field. The behaviour of these sensors in rotating magnetic fields was simulated using a micromagnetic simulator. The structures were used for microcompass and contactless potentiometer applications. The measurement system is computer controlled.

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1. Introduction

Magnetoresistance effect (MR) which arises in 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). 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. Because of the AMR effect will appear an electric field perpendicular to the applied current even when the magnetic field is in the film plane. This is the so-called planar Hall effect (PHE). Using a Hall effect geometry 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 the relation [1]:

$$U = CM^2 j \sin 2\theta \equiv A \sin 2\theta \qquad (1)$$

where C is a constant determined by the material properties, j is the current density, M is the saturation magnetization and θ 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.

The PHE effect can provide information about the magnetic properties of the material and allows building of low-cost rotation sensors.

In this work we used three samples to study the angular dependence of the AMR effect: (i) a $Ni_{80}Fe_{20}$(10 nm) film, (ii) a $Ni_{80}Fe_{20}$(10 nm)/Cu(4 nm)/$Ni_{80}Fe_{20}$(10 nm) multilayer structure and (iii) a $Ni_{80}Fe_{20}$(2 nm)/Al_2O_3 (1 nm)/$Ni_{80}Fe_{20}$(2 nm) nanogranular film. The multilayer structure presents, in addition to the AMR effect, the GMR effect.

We observed some distortions of the angular dependence of the PHE voltage at low magnetic fields in the case of the ML structure. This is because the PHE voltage depends on the angle between the current and magnetization vector and, at low magnetic fields, the magnetization vector cannot follow accurately the direction of the applied magnetic field. We confirmed this behaviour by micromagnetic simulations.

2. Experimental

The samples were grown on Si substrates by thermal deposition. In what follows we give some details regarding the deposition of the Py(2 nm)/Al_2O_3(1 nm)/Py(2 nm) ML. First was deposited the (bottom) Py(2 nm) layer and then the Al(1 nm) layer. The Al_2O_3 insulating layer was formed by oxidation of the Al layer in air at 2 Torr and 50 °C for

60 minutes. Because the 2 nm Py layer is slight above the percolation limit [2] his surface is very rough. The rms surface roughness is about 1.5 nm which is more than the thickness of the Al_2O_3 insulating layer. Finally we deposited on to Al_2O_3 the second (top) layer of Py(2 nm). In this way we obtained a structure which is a mixture between Py and Al_2O_3 layers. We used a circular shape deposition mask with approximately 5 mm in diameter. The lead setup and the equivalent resistor arrangement model [3] are presented in Fig.1.

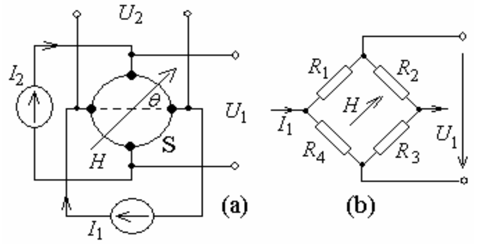

Fig. 1. (a) Schematic setup used for PHE measurements and (b) the four-resistor arrangement model to account for the electric behaviour of the sample. H is applied in the sample plane.

The four-lead setup consists of 4 Cu strips forming a square of 4 mm each side, like in Fig. 1(a). The current sources I_1 and I_2 drive the same current I through the sample, S, and are computer controlled. When the source I_1 is on, the source I_2 is off, the measured voltage is U_1. When the source I_2 is on, the source I_1 is off, the measured voltage is U_2. In this way, for a given angle, θ, between the magnetic field, H, and the direction of the current driven by I_1, we made two measurements for the PHE. Because for an ideal experimental setup $U_1=U_2$ we will take as reference for angle measurements the direction of the current I_1 for both measurements. This is because in equation 1, $\sin 2\theta$ becomes $\sin 2(\pi/2-\theta)$, see Fig.1(a). The measurement system is composed from a two channel instrumentation amplifier, a LabJack DAQ card and a NI 4351, 24 bit, DAQ card for high resolution readings. When $\theta=0$, the PHE voltage has a minimum because the MR effect will have the same amplitude and sign for all the resistors from the equivalent Wheatstone bridge. However, the PHE voltage is not zero, for $\theta=0$, because of the residual offset (misalignment of the contacts) and because the magnetization is not following accurately the direction of the magnetic field. When $\theta=45°$, like in Fig.1, the resistors $R_{1,3}$ will experience a positive MR effect (longitudinal MR) whereas the resistors $R_{2,4}$ will experience a negative MR effect (transversal MR) and the PHE will have a maximum value. This measurement configuration increases the AMR effect.

3. Results and discussion

Fig. 2 presents the angular dependencies of the PHE effect, voltage U_1, for the investigated samples. This means that the source I_1 is ON and the source I_2 is OFF. The angle θ between the applied magnetic field and the direction of the current I_1 is illustrated in Fig. 1(a). Because of the contacts misalignments the angular behaviour of the PHE, voltage U_1, is distorted.

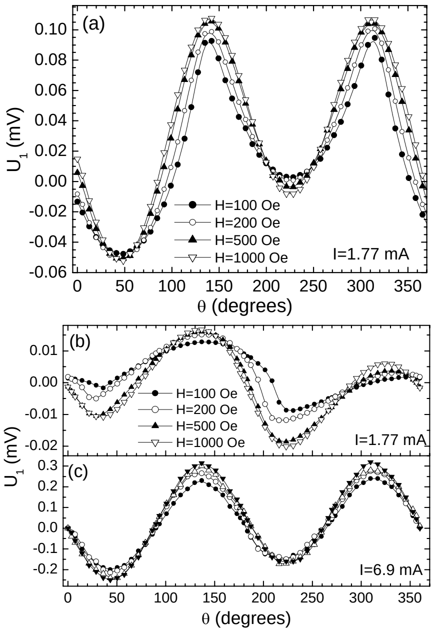

Fig. 2. Angular dependencies of the PHE effect, for different values of the applied field, measured for (a) $Ni_{80}Fe_{20}$(10 nm) film, (b) $Ni_{80}Fe_{20}$(10 nm)/Cu (4 nm)/$Ni_{80}Fe_{20}$(10 nm) ML and (c) $Ni_{80}Fe_{20}$ (2 nm)/Al_2O_3(1 nm)/$Ni_{80}Fe_{20}$ (2 nm) nanogranular film.

We see that for the ML sample, Fig. 2(b), the angular dependencies of the PHE voltage for low magnetic fields (H=100 and 200 Oe respectively) present some irregularities and are far from the shape predicted by the equation 1. This is because the magnetization cannot follow accurately the direction of the magnetic field due to the coupling between the magnetic layers through the Cu layer. We present, in Fig.3, a micromagnetic simulation of the angular dependencies of the ML magnetization for different values of the rotating magnetic field.

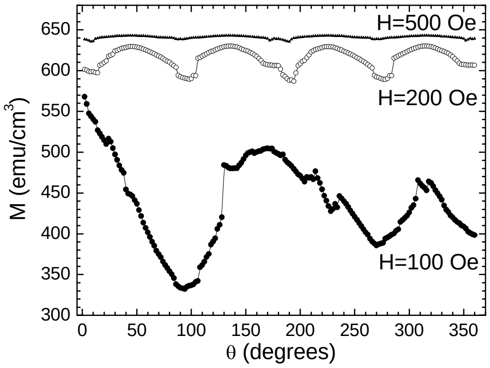

Fig. 3. A micromagnetic simulation of the angular dependence of the magnetization for the $Ni_{80}Fe_{20}$(10 nm)/Cu(4 nm)/$Ni_{80}Fe_{20}$(10 nm) ML structure.

To make these simulations we used a complex structure of single domains of Permalloy which interact between them and with the applied magnetic field [4]. As we can see from Fig. 3, the magnetization of the ML structure follows the direction of the magnetic field when $H \geq 500$ Oe. The angular dependencies, Fig. 2(b), of the PHE are almost the same for H=500 and 1000 Oe respectively. The small differences between the curves for the NiFe(10 nm) film, Fig. 2(a), show us that the sample saturates for fields higher than 100 Oe and the magnetization follow the direction of the magnetic field.

Fig. 4 presents three pictures of the magnetic moments orientation, in the ML structure, taken during the micromagnetic simulation when the rotating applied field was 100 Oe. The field starts to rotate from $\theta=0$ and makes a complete rotation. These pictures, Fig. 4, illustrate the fact that the magnetic moments cannot follow the applied magnetic field orientations as we can see for $\theta=45$, 90 and 180 degrees.

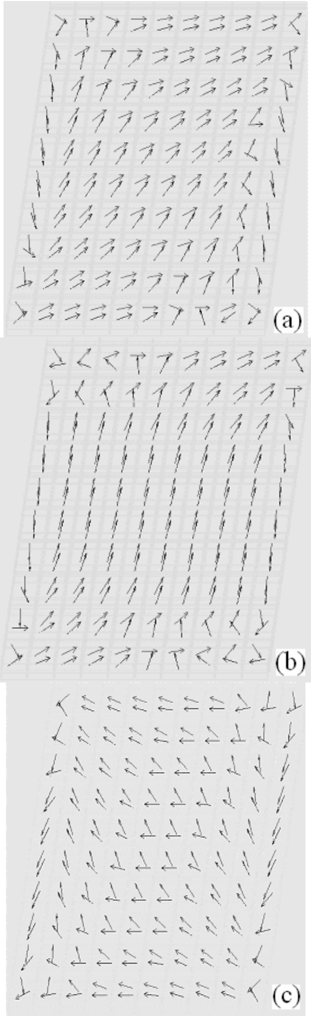

Fig. 4. The micromagnetic simulation regarding the orientation of magnetic moments in a $Ni_{80}Fe_{20}$(10 nm)/Cu(4 nm)/$Ni_{80}Fe_{20}$(10 nm) ML structure when the applied magnetic field, H=100 Oe, makes (a) 45°, (b) 90° and (c) 180° with the direction of the current I_1, starting from $\theta=0$.

Despite of the good response of the $Ni_{80}Fe_{20}$(2 nm)/Al_2O_3/$Ni_{80}Fe_{20}$(2 nm) nanogranular film the thermal stability is not good because of the conduction mechanism through the oxide barriers which give us a negative thermal coefficient of the resistivity.

To compensate the errors due to contacts misalignment and to increase the sensor sensitivity we made two measurements of the PHE for each angle over two orthogonal directions using the setup presented in Fig. 1(a). Other authors use two orthogonal PHE sensors [5] and make the same kind of measurements in order to improve the angular resolution. Making the PHE measurements for Permalloy and the ML structure over these two orthogonal directions we obtained by summating the voltages U_1 and U_2 a response of the sensor which is well described by the Eq. (1). The results of these measurements performed on $Ni_{80}Fe_{20}$(10 nm) and $Ni_{80}Fe_{20}$(10 nm)/Cu(4 nm)/$Ni_{80}Fe_{20}$(10 nm) sensors are presented in Fig. 5.

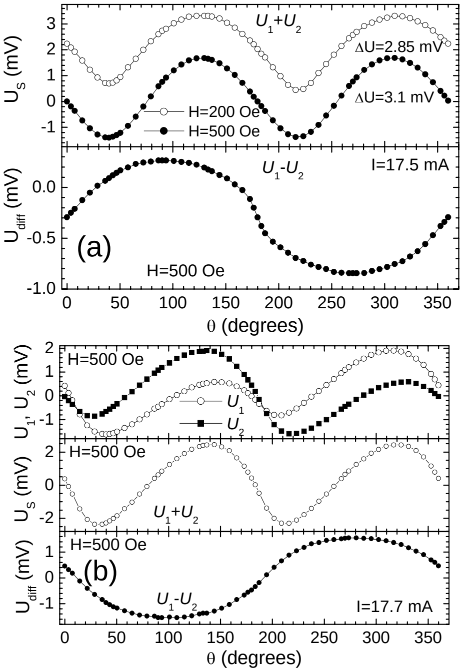

Fig. 5. The results of the angular dependencies of the PHE measurements made over two orthogonal directions for (a) $Ni_{80}Fe_{20}$(10 nm) thin film and (b) $Ni_{80}Fe_{20}$(10 nm)/Cu(4 nm)/$Ni_{80}Fe_{20}$(10 nm) multilayer structure.

The calculated values $U_S=U_1+U_2$ give us the output of the microcompass sensor with a sinusoidal behaviour with two periods for a complete rotation. For contactless AMR potentiometer application we placed a permanent magnet beneath the Si substrate at a distance of 0.1 mm. The magnet is a flat square of dimensions 2 x 6 x 6 mm^3 and provides a field of about 300 Oe through the entire sensor. To explain the behaviour of the difference voltage, $U_{diff}=U_1-U_2$, which give us a single period sinusoid for a complete rotation we have to look at dependencies U_1 and

U_2 from the Fig. 4(b). We believe that this voltage arises from the contacts misalignment errors.

4. Conclusions

We studied the angular response of the PHE for three systems: (i) $Ni_{80}Fe_{20}$(10 nm) film, (ii) $Ni_{80}Fe_{20}$(10 nm)/Cu(4 nm)/$Ni_{80}Fe_{20}$(10 nm) multilayer structure and (iii) $Ni_{80}Fe_{20}$(2 nm)/Al_2O_3(1 nm)/$Ni_{80}Fe_{20}$(2 nm) nanogranular film and by micromagnetic simulations we show the origin of the distortions which can be seen for low magnetic fields. By making PHE measurements over two orthogonal directions for each angle, we were able to compensate the errors that appear due to contact misalignments and homogeneity defects. This method can be used for microcompass application.

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[*] Corresponding author: volmer@unitbv.ro