Spin-valve structures with anisotropic magneto-resistance (AMR) for planar Hall effect (PHE) sensing applications

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We investigate the magneto-transport properties, the anisotropic magneto-resistance (AMR) and planar Hall effect (PHE) of the spin valve (SV) structures of Ta(3)/FeMn(10)/FMP(t_P)/Cu(2)/FMF(t_F)/Ta(3)(nm) with the ferromagnetic pinned (FMP) layer with thickness t_P =5, 7, 10 nm and the ferromagnetic (FMF) free layer of Permalloy of thickness t_F =6, 10 nm deposited by Magnetron Sputtering. The exchange biasing induced from the interface between the pinned layer and antiferromagnetic FeMn layer can enhance the coupling strength between pinned Co layer and free Permalloy (Py) layer, and hence, the field sensitivity of the PHE is increased, even in the absence of external biasing field.

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1. Introduction

The planar Hall effect (PHE) together with the anisotropic magnetoresistance (AMR) effect are very powerful tools for characterizing magnetic thin films and multilayers. The sensitivity of the AMR signal measured along the longitudinal direction is, however, limited by Johnson noise originating from thermal fluctuations. The flaws associated with longitudinal AMR effects can be greatly improved by measuring the voltage change in the transverse direction instead, a phenomenon known as the planar Hall effect (PHE) extensively described in [1]. PHE is induced from spin-orbit coupling and spin polarization of the materials.

Multilayer structures with planar Hall effect (PHE) have been studied for applications such as field sensing [1-2], magnetic random access memory [3] or biosensors for detecting super-paramagnetic beads [1, 4–6], due to linearly response to applied magnetic fields below the saturation magnetization. Nguyen Van Dau et al. [2] studied a single NiFe layer thin film as a PHE sensor material. To induce the anisotropy of NiFe layer, they developed a current bar on top of the sensor junction. However, the problem of high power consumption and the heat generation during the performance limits its application for sensors.

For a PHE sensor, the condition for high field sensitivity is that the PHE voltage would have high amplitude at small magnetic field. These parameters are proportional to the active current passed through the active layer and the exchange coupling of multilayer thin films, respectively. In the bilayer structure as [5], the exchange coupling established at interface between ferromagnetic (FM) layer and antiferromagnetic (AF) layer is strong, in order of hundreds of Oe, which limits the field sensitivity of the PHE sensor.

The PHE is related to the rotation process of magnetic domains. As GMR effect, the planar Hall effect one expect to be larger for exchange coupling biased structures, because they can ensure a sufficient uniaxial anisotropy with well-defined single domain state to introduce a unidirectional anisotropy.

In a single domain approximation, the PHE voltage is determined by $U_{PHE} = CM^2\, j \sin 2\theta$, where C is a constant determined by the structure properties, j is the current density, M is the saturation magnetization and 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 [7, 8].

The spin valve structure consists of a non-magnetic metal sandwiched between two ferromagnetic layers, one of which is fixed (pinned) by an antiferromagnetic layer which acts to raise its magnetic coercivity and behaves as a hard magnetic layer, while the other layer is free and behaves as a soft magnetic layer. In the spin valve structure exchange coupling induced from the interface between ferromagnetic (FM) and antiferromagnetic (AF) layers can enhance the single domain state of NiFe layer, constrain the magnetization in coherent rotation, and prevent Barkhausen noise associated with magnetization reversal and thermal instability [9].

In this work we study a planar Hall effect (PHE) sensor based on spin valve (SV) structures. The experimental results revealed that the sensitivity increases with the decreased thickness of ferromagnetic pinned layer (FMP) of cobalt. The pinned ferromagnetic layer tends to keep the orientation of free permalloy layer even in absence of external biasing field, and the sensitivity of PHE sensor is increased.

2. Experimental procedure

The spin valve (SV) structures of the type $Si/SiO_2/Ta(3)/FeMn(10)/(FMP)(t_P)/Cu(2)/(FMF)(t_F)/Ta(3)$ (nm), where antiferromagnetic (AF) layer was FeMn of 10 nm thickness; ferromagnetic pinned (FMP) layer was Co with thickness t_P =5, 7 nm or Permalloy ($Ni_{80}Fe_{20}$ - simply Py) with thickness t_P =10 nm. Ferromagnetic free (FMF) layer was Permalloy with thickness t_F =6, 10 nm. All the layers were deposited by UHV Magnetron Sputtering, ATC2200 AJA, with the base pressure of $0.5x10^{-7}$mBar and argon pressure of $5x10^{-3}$mBar. The thickness of the Cu layer (2 nm) was chosen in order to: (i) assure a net separation between FMP and FMF layers, i.e. without bridges between them, (ii) introduce a small shunting effect of the sensing current which is flowing through the structure and (iii) to have a small magnetostatic coupling between FMP and FMF layers. It was found that 1.5 nm for the Cu layer can fulfil these requirements [1].

The SV structures were deposited using the masks of disk shape with diameter of 4 mm. The structures were connected to the external electronic circuitry by four Au strips (200 nm thickness) forming a square of 3 mm each side, disposed as is shown in Fig. 1.

The coercivity (H_C), the exchange bias field (H_{EB}) and magnetic moment were evaluated from VSM hysteresis loops, measured with the „7T Mini Cryogen Free Measurement System" - Cryogenic LTD.

The roughness of FMP layers and FMF layers were measured by Atomic Force Microscopy (AFM) using a Quesant Instrument Corporation-type Nomad equipment.

For magnetoresistance and PHE characterization, 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 with a Lake Shore 475 DSP gaussmeter. The schematics of the electrical circuit, used to perform the measurements on the SV samples, (Fig. 1).

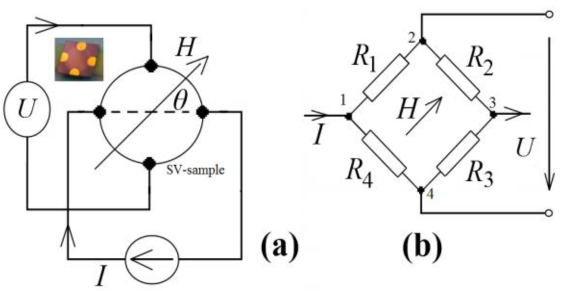

Fig. 1. (a) The connection of the SV-sample in the measurement circuit and (b) the equivalent circuit; the angle between the driving current and the applied magnetic field is denoted with θ

In Fig. 1 is presented the typical planar Hall effect setup, but other two configurations can be used to investigate the AMR effect: (i) the current, *I*, is applied between contacts 1-2 and the voltage, *U*, is measured between contacts 3-4 and (ii) the current is applied between the contacts 1-4 and the voltage is measured between contacts 2-3. If *H* makes an angle of 45° with the direction of the driving current, $R_{1,3}$ will be parallel with *H* whereas $R_{2,4}$ will be perpendicular. Making the measurements using these two configurations the longitudinal and transversal behaviour of the MR effect can be derived [10]. The configuration, presented in Fig. 1, is equivalent with a Wheatstone bridge and gives a voltage which enhances the AMR effect. All the measurements were made using a driving current of 10 mA.

Finally, the low field measurements were made using a system composed from a small electromagnet with very low coercivity and a coil inserted in the gap of this electromagnet. The field generated by the electromagnet is perpendicular on the field generated by this coil. The electromagnet was used to supply a polarizing field, H_{bias}, whereas the coil was used to generate small magnetic fields, *H*, in order to measure the PHE signal. The sample was introduced inside of this coil and the driving current was parallel with H_{bias}.

3. Results and discussion

Three SV structures were investigated using the setup presented in Fig. 1. They will be denoted as follows:

- S_1: $Si/SiO_2/Ta(3\ nm)/\ Fe_{50}Mn_{50}(10\ nm)/Py(10\ nm)/Cu(2\ nm)/Py(6\ nm)/\ Ta(3\ nm)$;
- S_2: $Si/\ SiO_2/Ta(3\ nm)/Fe_{50}Mn_{50}(10\ nm)/Co(7\ nm)/Cu(2\ nm)/Py(10\ nm)//Ta(3\ nm)$;
- S_3: $Si/\ SiO_2/Ta(3\ nm)/Fe_{50}Mn_{50}(10\ nm)/Co(5\ nm)/Cu(2\ nm)/Py(10\ nm)//Ta(3\ nm)$.

Where Py denotes $Ni_{80}Fe_{20}$ (Permalloy).

Fig. 2 shows the 3D image of atomic force microscopy (AFM) for the sample Py=10 nm deposited on Si /SiO_2/; the roughness is R_{rms}= 0.5 nm.

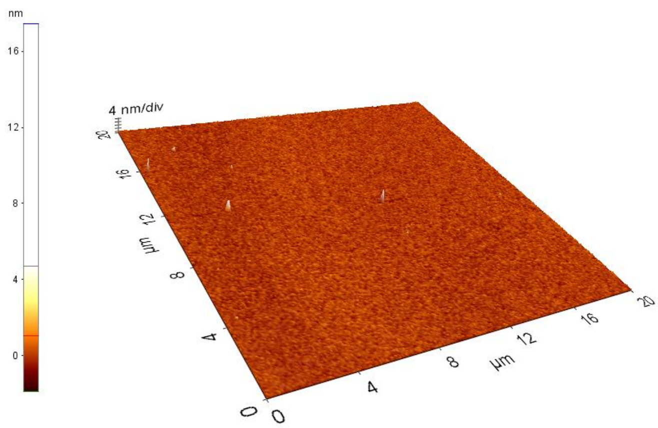

Fig. 2. The 3D image of AFM for the sample Py=10 nm deposited on Si /SiO_2

Fig. 3 shows the 3D image of AFM for the sample Co=7 nm deposited on Si /SiO_2/; the roughness is R_{rms}= 2.1 nm.

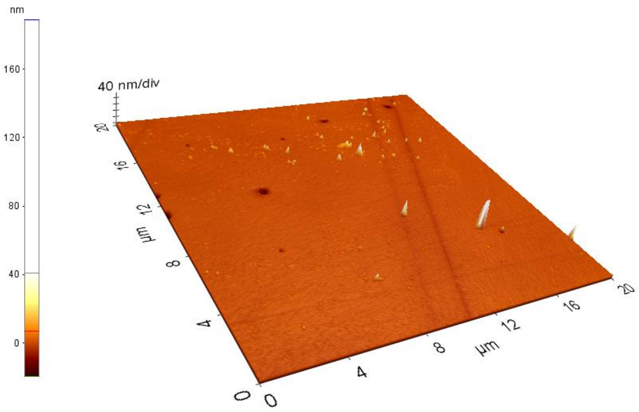

Fig. 3. The 3D image of AFM for the sample Co=7 nm deposited on Si /SiO_2

Fig. 4 presents hysteresis loop of the bilayer Py (10)/Fe_{50} Mn_{50} (10) (nm). This bilayer FM/AFM has coecivity H_C=2626 A/m and exchange bias H_{EB}=2388 A/m. We can consider that is a good exchange coupling for SV structure application.

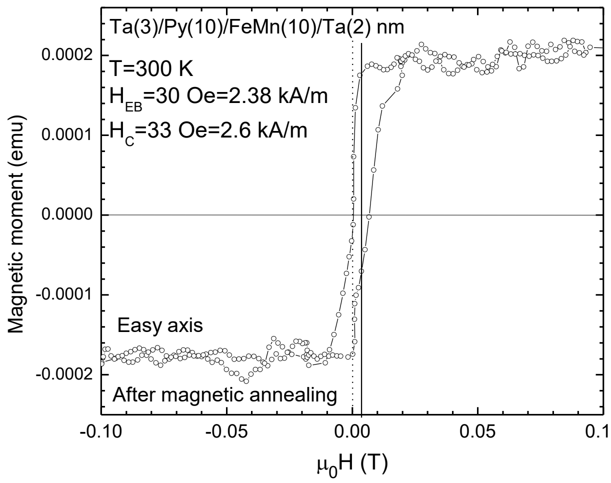

Fig. 4. Hysteresis loop of the Py(10nm)/FeMn (10nm) structure

The field dependence of the AMR signal for sample S_1 is presented in Fig. 5. Basically can be seen two steps, one at low fields (10 kA/m) which reveals the magnetization switching of the free layer and the other at higher fields (about 40 kA/m) when the pinned layer is switching his magnetization.

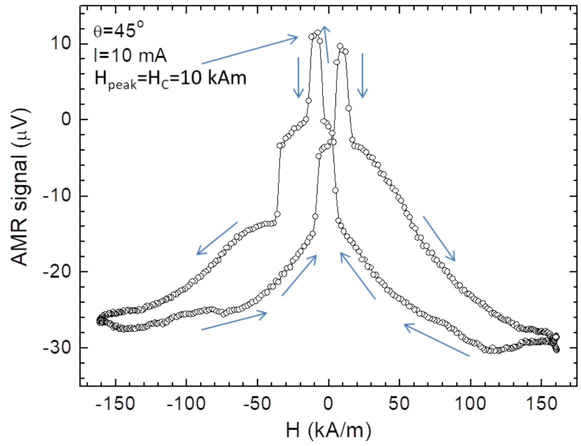

Fig. 5. Field dependence of the AMR effect for sample S_1 measured using the setup presented in Fig. 1. The arrows are guides for the eyes

The field dependences of the PHE voltage for sample S_1 without and with a biasing field of 4 kA/m are presented in Fig. 6.

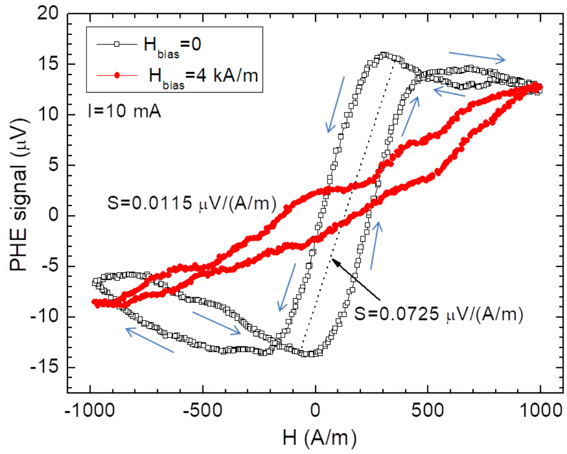

Fig. 6. The low field dependences of the PHE signal without and with a biasing field of 4 kA/m for sample S_1. The arrows are guides for the eyes

The pinning field and the initial film magnetization are parallel with the driving current. The applied field makes an angle of 90 degrees with the driving current and exerts a torque on the film magnetization.

In the case of SV structure S_1, when no biasing field is applied the signal saturates at very low fields and gives a sensitivity, in the linear region, of about 0.0725 µV/(A/m). A biasing field of 4 kA/m (about 50 Oe) increases the width of the linear region and decreases the hysteresis effects. The mean sensitivity is about 0.0115 µV /(A/m).

The samples S_2 and S_3 show typical field dependences of the longitudinal and transversal AMR effects. The field dependences of the AMR signal, for samples S_2 and S_3 are presented in Fig. 7 (a) and (b).

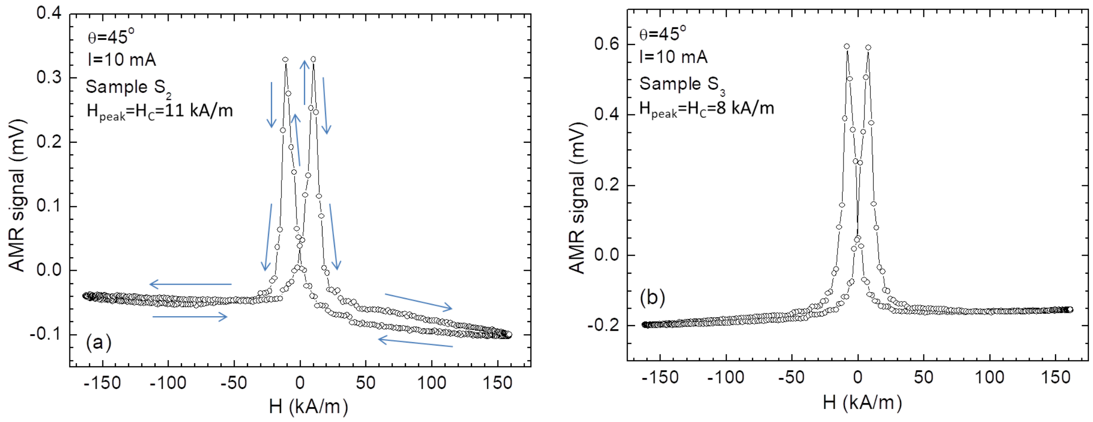

Fig. 7. Field dependences of the AMR signal for (a) sample S_2 and (b) sample S_3. The arrows are guides for the eyes

The SV structures of samples S_2 and S_3 are almost the same, which is reflected in the plots presented in Fig. 7. Only the thickness of the pinned Co layer differs and is, probably, responsible for the small difference between the peak positions: 10.5 - 11 kA/m for sample S_2 and 8 kA/m for sample S_3.

The low field dependence of the PHE signal is presented in Fig. 8 for both the samples S_2 and S_3. The measurements are made in the same conditions like for the sample S_1.

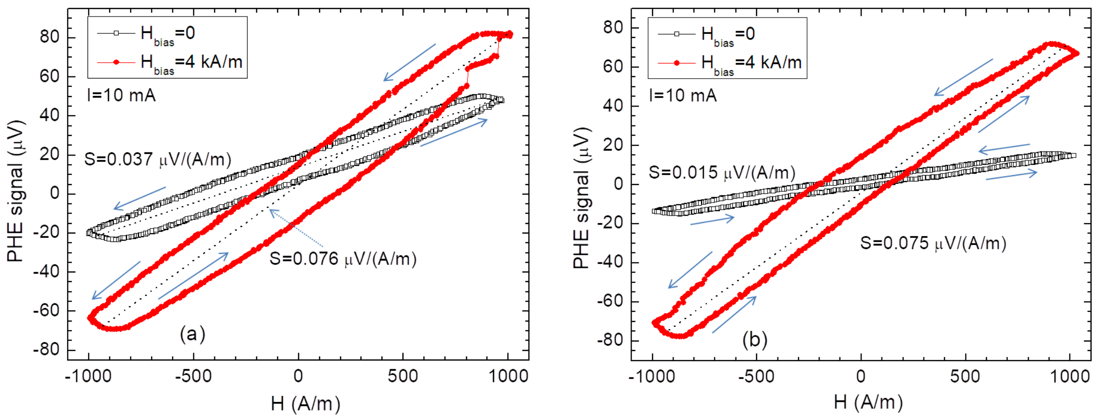

Fig. 8. Low field dependences of the PHE voltage for (a) Sample S_2 and (b) Sample S_3. The arrows are guides for the eyes

The differences appear only when no biasing field is applied and reveals the importance of strength coupling between the Co layer and the free Py layer (which is seen as the sensing layer). The thicker layer of Co (sample S_2) was able to maintain a higher magnetization state in the Py layer, which explains the higher values of the PHE signal observed for S_2 when H_{bias}=0. When the biasing field is applied, the magnetization state of the Py layer is almost the same in both the samples and no differences between the field dependences of the PHE signals can be seen. The filed sensitivities of the PHE investigated on these samples are not large but they are comparable with sensitivities reported in other works [1, 11] that are about 5-7 µV/Oe for spin valve structures. However, was found that a geometrical factor, larger than 1, can increase the magnitude of the measured PHE signal for sensors patterned with different shapes [1, 12, 13].

4. Conclusions

The anisotropic magnetoresistance (AMR) and planar Hall effect (PHE) of the spin valve (SV) structures of Ta(3)/FeMn(10)/FMP(t_P)/Cu(2)/FMF(t_F)/Ta(3)(nm) with the ferromagnetic pinned layer (FMP) of thickness t_F =5, 7, 10 nm and the ferromagnetic free (FMF) layer of thickness t_P =6, 10 nm, deposited on Si/SiO_2 were investigated.

The experimental results revealed that the sensitivity increases with the increased thickness of ferromagnetic pinned (FMP) layer of cobalt. The exchange coupling induced from the interface between pinned Co layer and antiferromagnetic FeMn layer can enhance the strength coupling between Co layer and free NiFe layer. The pinned ferromagnetic layer tends to keep the orientation of free ferromagnetic layer even in absence of external biasing field, and the sensitivity of sensor is increased, about 0.037 μV /(A/m).

The low roughness of magnetic layers enhanced the exchange interaction between ferromagnetic pinned layer and ferromagnetic free layer via thin Cu layer.

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