Journal of Optoelectronics and Advanced Materials Vol. 5, No. 4, December 2003, p. 951 - 957

HALL EFFECT IN PERMALLOY BASED THIN FILMS AND MAGNETIC MULTILAYERS

M. Volmer*, J. Neamtu[a]

Physics Department, Transilvania University, 29 Eroilor, Brasov 500036, Romania
[a]Research and Development Institute for Electrical Engineering, 313 Splaiul Unirii, 030138 Bucharest, Romania

The correlation between the Hall effect and sample magnetization enables the use of this technique for the study of magnetic properties in Permalloy (Py) thin films and Py/NM/Py multilayers. NM denotes Cu and Al_2O_3 layers. The measured voltages present hysteresis loops at low magnetic field and are very sensitive to the experimental setup. The saturation fields obtained when the magnetic field is applied normal to the film plane are less than the values predicted from the shape anisotropy known for flat surfaces, but are consistent with the film surface topography.

(Received July 4, 2003; accepted August 21, 2003)

Keywords: Hall effect, Magnetic films, Anisotropic magnetoresistance, Planar Hall effect

1. Introduction

Usually, the magnetic properties of the thin films are investigated using a Vibrating Sample Magnetometer (VSM) or other methods like Kerr effect magnetometry. A branch of microelectronics called spintronics requires novel magnetometric methods because conventional ones (torque magnetometry and VSM) become ineffective for small samples. In this connection, the use of the Hall effect becomes more attractive because can give us direct information regarding the magnetic properties of the thin films we investigate. In this study we use the Hall effect in conjunction with the magnetoresistance effect (MR) for the study of the magnetic properties of Permalloy (Py) and Py/NM/Py thin films

The Hall effect in magnetic materials is commonly described by the phenomenological equation [1,2]

$$\rho_H = R_0 B + R_S \mu_0 M \tag{1}$$

where ρ_H is the Hall resistivity, *B* the magnetic induction, and *M* the magnetization. R_0 is the ordinary Hall coefficient and R_S is the extraordinary Hall coefficient which usually is much larger (about 10 or 100 times) than R_0 so the Hall voltage can serve as a direct measurement of magnetization. On the other hand many magnetic thin films exhibit the in-plane anisotropic magnetoresistance effect (AMR) that is responsible for an electric field which can be detected perpendicular to the direction of the current when the magnetic field is applied in the film plane. This is the planar Hall effect (PHE) which together with the extraordinary Hall effect contributes to measured signal. Starting from 1995 there are reports regarding the so called giant Hall effect (GHE) which can be observed in co-sputtered granular magnetic metal-insulator samples when the magnetic metal volume fraction is in the range of 0.53-0.61 which is the percolation ratio for the metal-insulator transition [2-5]. The GHE was first observed in NiFe-SiO_2 composites [3] where R_S for $x \approx 0.53$ was found to be almost four

* Corresponding author: volmerm@unitbv.ro

orders of magnitude greater than the value for pure metal film. It is interesting to note that an enhancement of 700 of the ordinary Hall coefficient was observed in non-magnetic Cu-SiO_2 composites [6] with a structure close to that of NiFe-SiO_2 films. GHE was also observed in Ni-SiO_2 and Co-SiO_2 close to and on both sides of the metal-insulator transition.

2. Results and discussion

In this paper we present the Hall effect measurements made on a 10 nm Permalloy (Py) single layer, Py(t_{Py})/Cu(4 nm)/Py(t_{Py}) and Py(2 nm)/Al_2O_3(1 nm)/Py(2 nm) multilayers (MLs) where t_{Py}=4, 10 nm. The films with the above thicknesses were deposited by high vacuum evaporation onto oxidised Si substrates. The local surface topography was studied using atomic force microscopy (AFM). The magnetization measurements have been performed at room temperature using VSM. 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 [8] 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 is presented in Fig.1. This setup allows us to enhance or to minimize the influence of the AMR effect on the measured signal [7]. The DC current, I, was kept constant with accuracy better than 0.1 μA. **H** is the applied magnetic field which makes the angle θ with respect to the film plane; **n** is the surface normal. We denote with $\mathbf{H}_p$, the in plane component of **H** and with $\mathbf{H}_n$ the component of **H** which is normal to the sample plane. To maximize the effect of the PHE on the output voltage the in plane component of the magnetic field ($\mathbf{H}_p$) has to be applied at an angle α=45° respect to current direction, as shown in Fig. 1. In some cases the samples were rotated back (α=0°) in order to minimize the influence of the AMR effect on the Hall effect measurements. In this case the current, I, is parallel to $\mathbf{H}_p$.

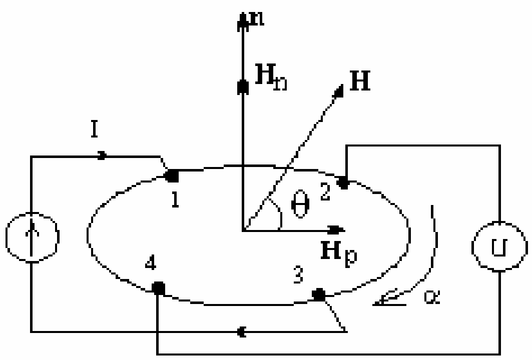

Fig. 1. Schematic diagram of the connections used in the Hall effect experiments. Also shown are the definitions of some of the angles used in this discussion. Here the angle between the current direction, I, and the in plane magnetic field, $\mathbf{H}_p$, is α=45°.

The AFM topography for a 4 nm permalloy thin film deposited on to oxidized Si substrate reveals a rough surface with a rms-roughness of 1.1 nm. The maximum height of the surface roughness was about 10.7 nm! These results are in agreement with other studies [8] regarding magnetoelectric properties of the Py/Cu/Py MLs when the evaporated thin Py layers are slightly above the percolation limit which is about 2 nm in the case of Si/SiO_2 substrate. Fig. 2 shows the field dependencies of Hall resistivity, ρ_H, for Py(t_{Py})/Cu(4 nm)/Py(t_{Py}) with t_{Py}=4 and 10 nm. The in plane hysteresis loop for a Py(4 nm)/Cu(4 nm)/ Py(4 nm) ML is presented in Fig. 2(b).

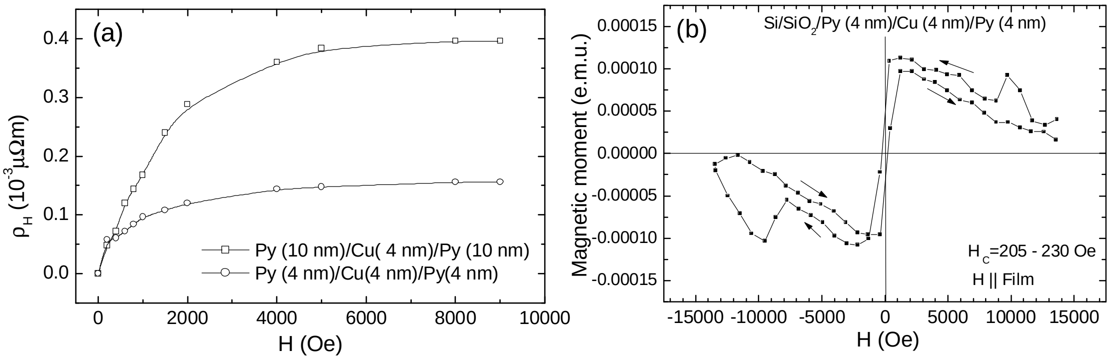

Fig. 2 (a) Field dependencies of Hall resistivity for two MLs with t_{Py}=4 and 10 nm and (b) in plane hysteresis loop for Py(4 nm)/Cu(4 nm)/ Py(4 nm) at room temperature.

The Py(4 nm)/Cu(4 nm)/Py(4 nm) sample presents distortions of the multilayer structure and intermixing between permalloy and Cu layers that alters the magnetic properties. The predominant conduction mechanism is diffusive scattering at interfaces, grain boundaries and defects that diminishes the MR and Hall effects. The MR ratio found is no grater than 0.08 %. When the Py thickness increases the film becomes uniform in microstructure. For a Py(10 nm)/Cu(4 nm)/Py(10 nm) ML the average roughness is low, 0.87 nm. The average grain size, D, is about 15 nm. The Hall resistivity is about four times grater than for the ML with t_{Py}=4 nm. For these reasons thermally evaporated metallic MLs with very thin Py layers and metallic nonmagnetic layer are not interesting for practical applications and in what follows the ML with t_{Py}=4 nm will be excluded from our discussion.

In Fig. 3(a) we present magnetic-field dependencies of the Hall resistance R_H ($\rho_H=R_H \cdot t$, where t is the thickness of the film) for the samples considered in this paper. The small asymmetries arise from the AMR and GMR effects that alter the shape of the Hall effect.

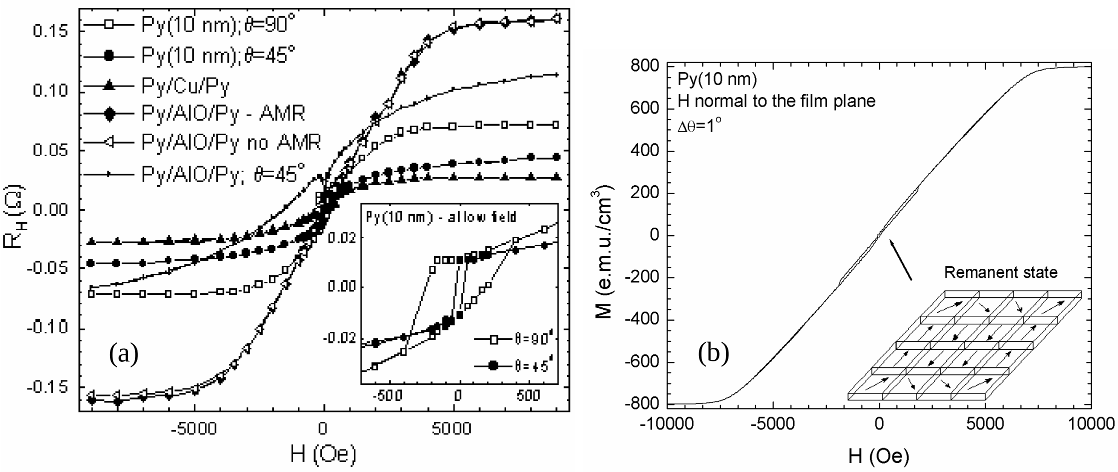

Fig. 3.(a) Field dependencies of the Hall resistance; for Py(10nm) was used a configuration that minimize the AMR effect and For Py/Cu/Py and Py/Al_2O_3/Py MLs were used both configurations, (b) Simulation of the remanent state for a collection of 4x4 single domains of Py(10 nm) when $\Delta\theta$=1°.

The saturated Hall resistivity increases from about 0.66 nΩ·m for the Py/Cu/Py ML to 0.97 nΩ·m for the Py/Al_2O_3/Py multilayer. The saturated Hall resistivity of the 10 nm Py film is about 0.72 nΩ·m. We can see in inset the hysteretic behaviour for the Py film at low magnetic fields for θ=90° and 45°. It is interesting to note that R_H takes almost the same values at H=0 for different orientations of the magnetic fields [9,10]. This means that the remanent magnetization of the Py film takes the same values. This behaviour was observed for all the samples we measured. The width of the hysteresis depends on the angle θ between the applied magnetic field and the film surface. The hysteresis amplitude depends on the amplitude of the AMR and GMR effects that exhibit our samples [2]. Because at low magnetic fields the shape anisotropy forces the magnetization to rotate in the film plane what we have is a PHE signal which can be used as probe of magnetization reversal. To explain the hysteresis that appears when θ=90 ° we have to admit, also, a slight misalignment (which we define as Δθ) between the film normal and the applied field. Although the angle Δθ could not be measured exactly it was less than 2° because we obtained the same field dependencies of the Hall effect for θ=90 ° and 90 °±2.5 °. This assumption was verified by a simulation of the remanent magnetization state for a 10 nm Py single layer and the result is shown in Fig. 3(b) where we can see the dipole orientations when Δθ=1° [9,10]. For angles Δθ>0° it is relatively easy to extract from the measured signal the contribution of the AMR effect which becomes very important when α=45º. The results where presented in [9,10,11,12] and we can see, also from Fig. 3(a), that the width of the hysteresis decreases when Δθ increases because increases the in plane component, H_P, of the magnetic field. The field at which the sample reaches the magnetically disordered state, H_C, decreases from about 280 Oe when Δθ=0 ° to about 80 Oe when Δθ=15 ° and 30 Oe when Δθ=90 °. When α=0º the influence of the AMR on the measured signal is very small and arises only from errors regarding the sample orientation and contacts misalignments. The hysteretic behaviour we observed for the field dependencies of the Hall effect can be explained if we consider the extraordinary Hall coefficient as a sum between a field-independent coefficient and a coefficient corresponding to the magnetically disordered state [2]:

$$\rho_H = R_0 B + (R_{S,sat} + R_{S,MR})\mu_0 M \quad (2)$$

where $R_{S,sat}$ is a field-independent extraordinary Hall coefficient corresponding to a magnetically saturated state at high magnetic field. $R_{S,MR}$ is a coefficient corresponding to the magnetically disordered state and is related to an additional (AMR and/or GMR) component of resistivity which becomes very important at low fields when the magnetisation reversal takes place. $R_{S,MR}$ reduces to zero in the magnetically saturated state.

For the Si/SiO_2/Py(10 nm)/Cu(4 nm)/Py(10 nm) ML we obtained for H_C values that ranged from 600 Oe when Δθ=0° to 200 Oe when Δθ=15° and 60 Oe when Δθ=90°. This increases of H_C compared with the single Py(10 nm) layer is due to a positive coupling between ferromagnetic layers through the nonmagnetic layer (Cu) that appears if the non-flatness of the layers is taken into account. Also we must consider the existence of the Py bridges through the Cu layer that produce a direct coupling between the adjacent Py layers. The Py/Al_2O_3/Py multilayer acts like a granular magnetic metal-insulator samples with a hysteresis width less than 10 Oe when the field is applied in the film plane and without hysteresis when the magnetic field is applied normal to the film surface. In fact we observe a very small hysteresis when the measurement configuration enhances the influence of the AMR effect but mainly the two curves are identical for all the values of the magnetic field.

Fig. 4 shows the angular dependencies of the voltage U for different values of the applied magnetic field for a Py(10 nm) single layer. The involved angles are explained in Fig. 1.

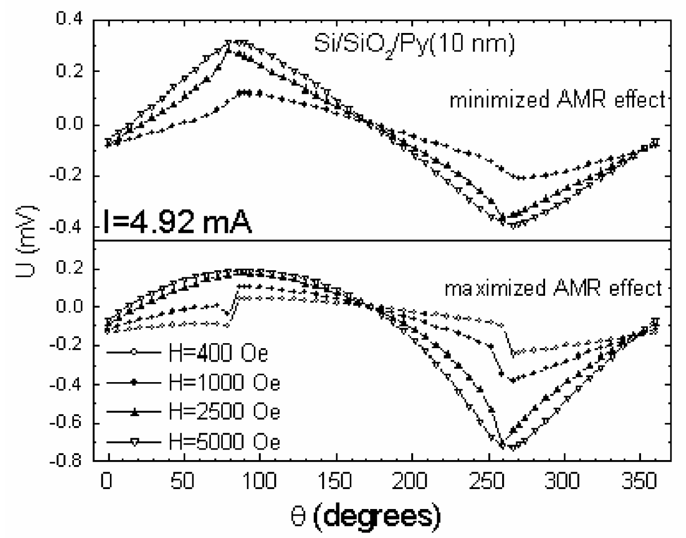

Fig. 4. The angular dependencies of the measured voltage U for a Py(10 nm) single layer; minimized AMR effect means **α**=0º and maximized AMR effect means **α**=45º.

The influence of the AMR effect on the measured voltage is reflected in the asymmetry of the data. For magnetic fields less then 400 Oe the magnetization stays only in the film plane and the signal is very small when α=0º. The negative peaks we observe for H<2000 Oe are due to the PHE and reflects the in plane magnetization reversal of the film i.e. the curves contain features which reflect the motion of the moments within the plane of the film. As we can se this behaviour cannot be observed when the experimental setup minimises the AMR effect. When H increases, the magnetization vector attempts to follow the field. The difference between the torque curves at H=2500 Oe and H=5000 Oe is very small. Using the data from Fig. 3(a) and Fig. 4 we obtain a saturation field H_S=3000 Oe which is less than the value predicted from the shape anisotropy (H_{S0}=10.5 kOe) known for flat surfaces. This reduction of the perpendicular anisotropy leads to a roughness effect [8-10] of about 9 nm which is in good agreement with the AFM measurements. This value can be estimated using the relation [8]:

$$H_S = H_{S0}\left[1 - \frac{3\delta(1-f)}{4d_{Py}}\right] \tag{3}$$

where δ is the mean roughness and f a function of the ratio of δ and the correlation length of the roughness; d_{Py} is the total thickness of the ferromagnetic layers (in the case of MLs). The roughness effect is expressed by $\delta(1\text{-}f)$, [8].

Finally, we present in Fig. 5 the angular dependencies of the Hall voltage for Py(10 nm)/Cu(4 nm)/Py(10 nm) and Py(2 nm)/Al_2O_3(1 nm)/Py(2 nm) multilayers. The presence of the Cu layer reduces the magnitude of the AMR effect in Py/Cu/Py ML. The peaks of the same sign (negative) that we observe for low magnetic fields when α=0° reveal the magnetization reversal that takes place in the film plane. For magnetic field H>4000 Oe the magnetization vector follows the rotation of the applied magnetic field. The saturation field is H_S=4000 Oe which leads to a roughness effect of about 5 nm. From Fig. 3 and Fig.5 we see an enhancement of the extraordinary Hall resistivity in Py/AlO/Py ML. This is in agreement with other studies of the extraordinary Hall effect in ferromagnetic-insulator mixtures in the vicinity of percolation threshold [2-6].

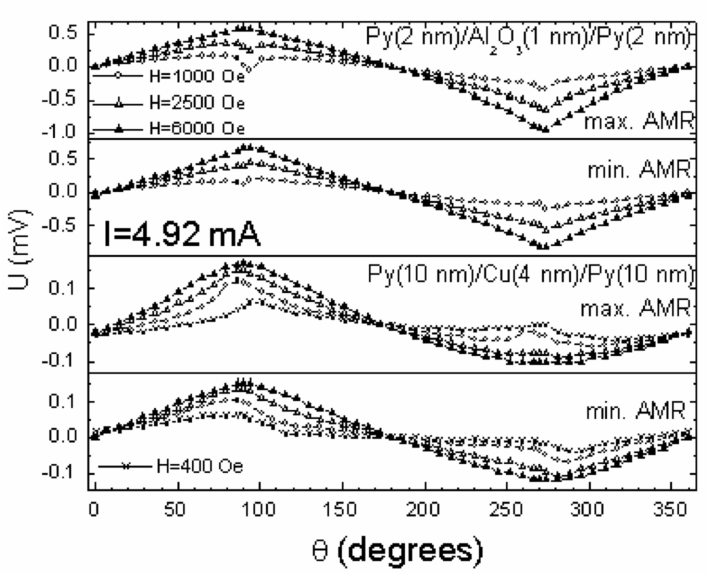

Fig. 5. The angular dependencies of the measured voltage U for Py/Cu/Py and Py/AlO/Py MLs.

The Py/AlO/Py film presents an improved linearity of the Hall signal in magnetic field and an improved sensitivity $dR_H/dB \approx 0.46\ \Omega/T$. The saturation field obtained from Fig. 3 and Fig. 5 is H_S=3850 Oe. The sharp peaks observed in low magnetic field when θ=90°→93.6° and when θ=270°→273.6° are produced by the magnetization reversal that takes place in the film plane.

In Fig. 6 we present the PHE measured in Py/AlO/Py thin film. The sensitivity is about 0.04 mV/Oe for a magnetic field variation less than 200 Oe and can be improved by a careful choice of the layers thicknesses and by increasing the precision of the measuring setup (contacts, shape).

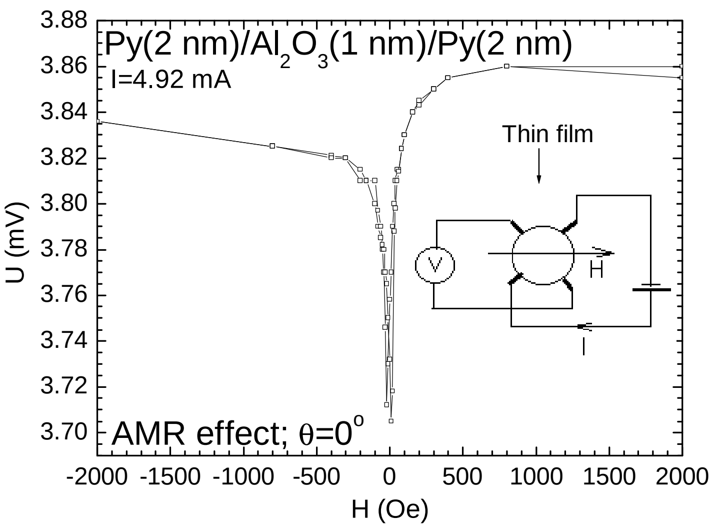

Fig. 6. Field dependence of the PHE for a Py/AlO/Py thin film near the percolation limit. In inset is presented the experimental setup.

4. Conclusions

Hall effect measurements on Py based single films and multilayers were used to investigate their magnetic properties. The use of the configuration that enhances the AMR effect can be useful for detection of the fields for which the magnetically disordered state is obtained. From these measurements we can estimate the film roughness and the coupling between the magnetic layers. This method can be a very useful tool in the characterization of the magnetization processes for a wide variety of technologically interesting thin magnetic films.

References

[1] F. Y. Ogrin, S. L. Lee, Y. F. Ogrin, J. Magn. Magn. Mater. **219**, 331 (2000).

[2] A. Gerber, A. Milner, M. Karpovsky, B. Lenke, H.-U. Habermeier, J. Tuaillon-Combes, M. Negrier, O. Boisron, P. Melinon, A. Perez, J. Magn. Magn. Mater. **242-245,** 90 (2002).

[3] A. B. Pakhomov, X. Yan, B. Zhao, Appl. Phys. Lett. **67**, 3497 (1995).

[4] J. C. Denardin, A. B. Pakhomov, et al. J. Phys. Condens. Matter **12**, 3397 (2000).

[5] J. C. Denardin, M. Knobel, X. X. Zhang, A. B. Pakhomov, J. Magn. Magn. Mater. **262**, 15 (2003)

[6] X. X. Zhang, H. Liu, A. B. Pakhomov, *ETOPIM-5* (Hong Kong, 1999) Physica B **279**, 81 (2000).

[7] C. Prados, D. Garcia, F. Lesmes, I. I. Freijo, A. Hernando, Appl. Phys. Lett. **67**, 718 (1995)

[8] T. Lucinski, G. Reis, N. Matern, L. van Loyen, J. Magn. Magn. Mater. **189,** 39 (1999).

[9] M. Volmer, J. Neamtu, I. Inta, J. Optoelectron. Adv. Mater. **4**(1), 79 (2002).

[10] J. Neamtu, M. Volmer, Mat. Res. Soc. Symp. Proc. Vol. 746 (2003).

[11] M. Volmer, J. Neamtu, J. Optoelectron. Adv. Mater. **5**(1), 319 (2003).

[12] M. Volmer, J. Neamţu, Magnetoresistance and Hall Effect Characterisation of Magnetic Multilayers, Proceeding, (e-book – CD-ROM), "Materials Week International Congress on Advanced Materials, their Processes and Applications", 30 Sept. – 2 Oct., 2002, Munich, Germany.