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Hall Effect and Magnetoresistance in Magnetic Multilayers with Alternating In-Plane and Out-of-Plane Anisotropies

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A direct comparison between the Hall effects and giant magnetoresistance of ferromagnetic multilayers of similar composition $(Ni_{80}Fe_{20}/Au/Co/Au)_N$ with alternating in-plane and out-of-plane magnetization direction of Co layers is presented. The characteristic features at magnetic field-dependence of giant magnetoresistance were correlated with the creation and annihilation of the stripe domains in Co layer, with perpendicular anisotropy. The nucleation field values were investigated as an Au layer thickness function. Furthermore, the *in situ* conductance measurement results characterised the island growth mode of the ferromagnetic layers. The percolation thicknesses were also indicated.

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1. Introduction

The ferromagnetic multilayered systems (Mls) attract much attention because of the giant magnetoresistance (GMR) existence and the applications in magnetic data storage devices. In particular, there is an interest in ferromagnetic multilayers with a strong perpendicular anisotropy [1, 2]. In the $(Py/Au/Co/Au)_N$ systems (Py stands for $Ni_{80}Fe_{20}$ and N denotes the number of repetitions), the Co layer may have the magnetization perpendicular to the samples plane if the Co thickness ranges from 0.4 nm to 1.2 nm [2]. For a thicker Co layer its magnetization remains in layers plane. Although much effort has been made to investigate such systems, yet there has been no direct comparison between the Hall effects in Mls of similar composition but with alternating in-plane and out-of-plane magnetic anisotropies, and solely in-plane anisotropies.

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Furthermore, the electronic properties of Mls strongly correlate with their crystalline and interface structure. It has been already presented that the scattering processes in multilayers are enhanced at the interfaces [3–6]. Moreover, the conductance G may be also affected by mixing of two adjacent layers. The partially amorphous phase formation is then possible [4–6]. In consequence, the G increase is disrupted. Therefore, to monitor and distinguish the growth modes of each layer and potential intermixing, the conductance measurements performed *in situ* during the deposition process may be performed.

2. Experimental details

A series of samples with different thicknesses of Py, Au, and Co was prepared with magnetron sputtering at oxidised Si(100). Hall and magnetoresistance measurements were carried out on [Py(2 nm)/Au(2 nm)/Co(d_{Co})/Au(2 nm)]$_6$ Mls with $0.6 \le d_{\mathrm{Co}} \le 1.5$ nm for Co layers with out-of-plane and in-plane magnetization direction. The magnetization directions of Py layers were always in-plane. In the examined Mls, with the Au layer thickness of $d_{\mathrm{Au}} = 2$ nm, the exchange coupling is weak. Hence, the magnetization reversal of Py and Co layers occurs almost independently [7]. Apart from Mls with alternating magnetization direction the dependence of GMR on the Au layers thickness was investigated with fixed $d_{\mathrm{Co}} = 0.8$ nm (perpendicular anisotropy). All Mls were measured in magnetic field range of ±2.5 T. The time-dependent *in situ* conductance measurements were performed during [Py(2 nm)/Au(2 nm)/Co(0.8 nm)/Au(2 nm)]$_{15}$ deposition.

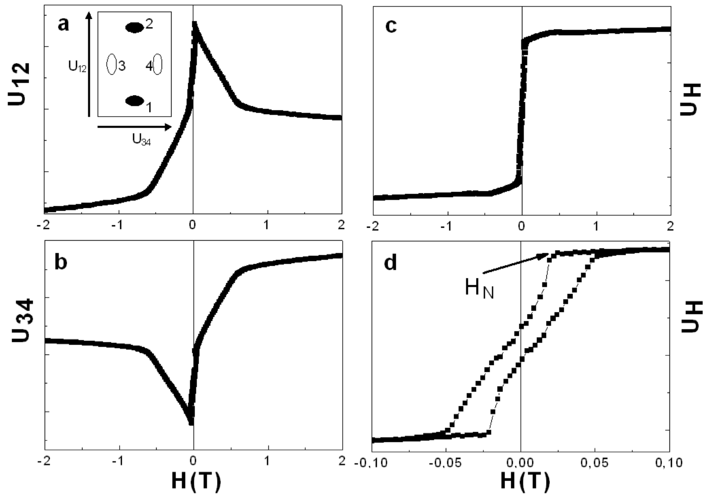

Fig. 1. The Hall voltage U_{H} measured in the van der Pauw geometry. (a) and (b) refer to the two perpendicular to each other directions of the measurement presented in a scheme in the inset. The Hall loop (c) was obtained by adding (a) and (b). Changing the scale (d) let the nucleation field H_{N} to be indicated. U_{H} in arbitrary units.

Since the anomalous Hall voltage is proportional to the perpendicular component of magnetization (M) therefore the plot of this voltage versus applied magnetic field H can be used to determine the magnetization reversal for $H_{\perp}$. If M has the in-plane component as well (alternating in-plane and out-of-plane anisotropies), the Hall signal will be the superposition of the real Hall and the so-called "planar Hall" voltages. The van der Pauw method is used to remove the "planar Hall effect" from the Hall signal. This method uses geometrical averaging, hence two signals U_{12} and U_{34} in Fig. 1a and b are measured perpendicularly to each other and added (Fig. 1c and d). Then, the "real" Hall voltage U_{H} is obtained without any residual magnetoresistance values.

The GMR was measured with the standard four-point probe in current-in-plane geometry. All the measurements were performed at the room temperature.

3. Results

The GMR(H) effect (H was perpendicular to the Mls planes) and $U_{\mathrm{H}}(H)$ for the [Py(2 nm)/Au(2 nm)/Co(0.8 nm)/Au(2 nm)]$_6$ Ml is displayed in Fig. 2a. Such a structure represents Mls with alternating in-plane (Py) and out-of-plane (Co) magnetic anisotropies. In this case, presented Hall loop is typical of thin films with the easy axis magnetization perpendicular to the sample plane. At a field H_{N} for which the stripe domains are nucleated a characteristic kink is observed. The existence of the stripe (or labyrinth) domains has been observed by magnetic force microscopy measurements [7]. The location of H_{N} field correlates perfectly well with maximal GMR(H) values. Magnetic domains annihilate at the magnetic field $H_{\mathrm{S}}^{\mathrm{Co}}$ (the saturation field of Co layers). In Fig. 2 the creation and annihilation of the domains lead to the appearance of the characteristic features observed in the GMR(H) dependence.

Figure 3 displays the values of H_{N} fields determined from the Hall effect for [Py(2 nm)/Au(2 nm)/Co(d_{Co})/Au(2 nm)]$_6$ Mls versus d_{Co} ($d_{\mathrm{Co}} < 1.2$ nm). In the same plot also the H_{Z} field values extracted from GMR(H) dependences are shown. The H_{Z} field is the magnetic field which supports the same angle between Py and Co magnetization directions as at the remanence. Both H_{N} and H_{Z} fields values correlate and increase with increasing Co layer thickness. However, their values decrease with thicker Au layer. Figure 4a and b presents the $H_{\mathrm{N}}(d_{\mathrm{Au}})$ and $H_{\mathrm{Z}}(d_{\mathrm{Au}})$, respectively, for Mls with $d_{\mathrm{Co}} = 0.8$ nm (perpendicular anisotropy). This situation reflects the influence of interlayer exchange coupling between Co and Py layers due to the domains creation and annihilation.

Figure 2b shows the results of similar measurements performed for [Py(2 nm)/Au(2 nm)/Co(1.5 nm)/Au(2 nm)]$_6$ Ml. In this case however, the magnetic easy axis of Co layers remains in layers planes. For Ml with $d_{\mathrm{Co}} > 1.2$ nm (Fig. 2b) the Co layers (as well as Py) exhibit in-plane anisotropy and the $U_{\mathrm{H}}(H)$ and GMR(H) characteristics differ from the ones for Mls with $d_{\mathrm{Co}} \leq 1.2$ nm. Therefore, the two independent saturation fields $H_{\mathrm{S}}^{\mathrm{Co}}$ and $H_{\mathrm{S}}^{\mathrm{Py}}$ of the Co and

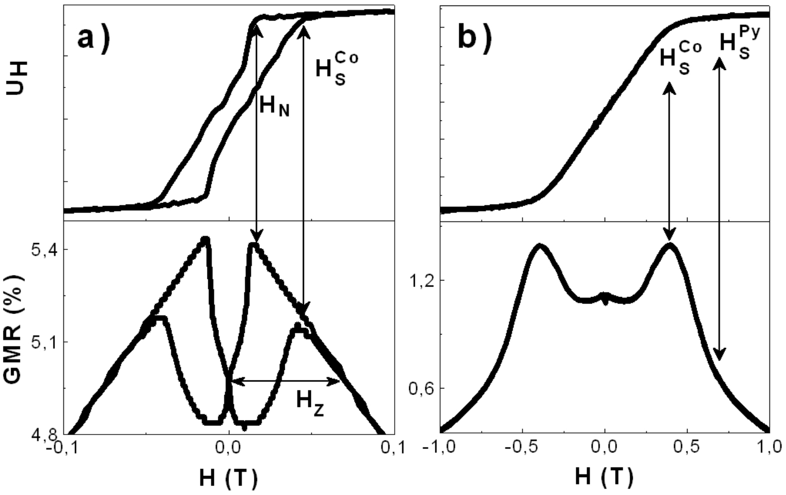

Fig. 2. The low field dependences of Hall voltages and GMR effects of the [Py(2 nm)/Au(2 nm)/Co(d_{Co})/Au(2 nm)]$_6$ Mls with $d_{\mathrm{Co}} = 0.8$ nm (a) and $d_{\mathrm{Co}} = 1.5$ nm (b). Let us note the different H scales in (a) and (b).

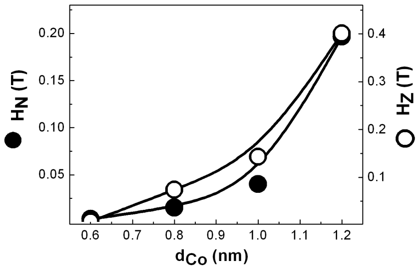

Fig. 3. The H_{N} and H_{Z} field values extracted from the Hall effect and GMR(H) of [Py(2 nm)/Au(2 nm)/Co(d_{Co})/Au(2 nm)]$_6$ Mls, with alternating in-plane and out-of-plane anisotropies, versus Co layer thickness.

Py layers, respectively, are distinguishable, both in the $U_{\mathrm{H}}(H)$ and in GMR(H) dependences.

The *in situ* $G(t)$ measurements carried out during the multilayers growth process resulted in the step-like dependence. The $G(t)$ structure originates from multilayered composition of the sample and relates to scattering processes occurring at the interfaces [3–6]. A detailed insight into the $G(t)$ evolution during the deposition process reveals different $G(t)$ behaviour for Py, Au and Co from the [Py(2 nm)/Au(2 nm)Co(0.6 nm)/Au(2 nm)]$_{15}$ growth (Fig. 5). Initially, Py forms islands at Si substrate, which have no influence on $G(t)$, as long as the layer is not a continuous one. After the percolation threshold, when a complete layer is formed, $G(t)$ increases. While Py at Au surface is deposited, at first Py islands are formed and grow laterally, creating subsequently a continuous layer. The in-

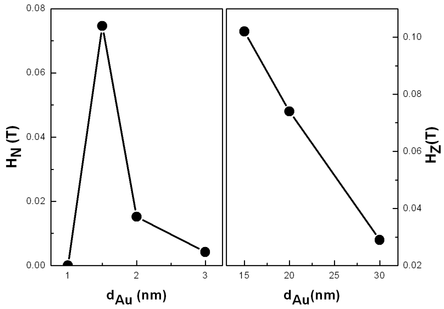

Fig. 4. The H_{N} and H_{Z} dependence on the Au layers thickness in [Py(2 nm/Au(d_{Au})/Co(0.8 nm)/Au(d_{Au})]$_6$.

complete Py layer at Au surface diminishes G by the enhanced surface scattering processes. The measurements indicate Py to grow in an island growth mode up to 0.35 nm. After the continuous layer formation the conductance increases. Similarly, Co forms islands on Au up to 0.24 nm of deposited Co, and afterwards a continuous Co layer is created.

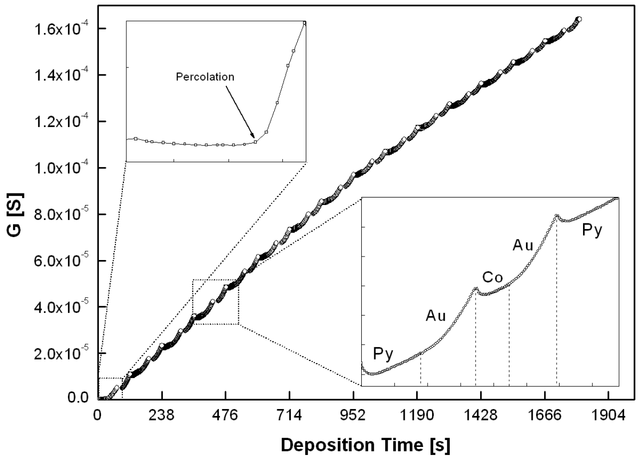

Fig. 5. The conductance G vs deposition time of [(Py(2 nm)/Au(2 nm)/Co(0.6 nm)/ Au(2 nm)]$_{15}$ measured *in situ* during deposition process. The percolation takes place at $d_{\mathrm{Py}} = 1.33$ nm.

At the early stage of Au layers growth (on both Py and Co), there is no clear evidence of the island growth mode, however, the $G(t)$ slope is changed. The presented conductance evolution in relation to the growth modes is independent of the number of repetition. It is worth mentioning that the local decreases in the $G(t)$ which occur in the early stages of the Py and Co layers growth on Au may also originate from the intermixing processes at interfaces. Similar measurements proved the total $G(t)$ to lose its growing tendency and to head to some kind of saturation because of the intermixing [8]. However, in the case of (Py/Au/Co/Au) Mls it is not observed. Hence the intermixing processes are inconsiderable.

4. Conclusions

The $(\mathrm{Py/Au/Co/Au})_N$ Mls with the perpendicular anisotropy of the Co layer have been examined. The values of the nucleation field H_N of stripe domains and the field H_{Z} which supports the same angle between Py Co magnetisation direction as at the remanence, have been extracted from the Hall and GMR measurements. Both were found to decrease with increasing Au layer thickness. The situation reflects the influence of the interlayer interaction between Co and Py layers because of the existence of the domain structure and the interlayer exchange coupling. We show that the appearance of the characteristic features at low fields in the GMR(H) is connected with the creation and annihilation of the stripe domains in Co layers with perpendicular anisotropy.

The conductance measurements performed *in situ* during the growth process allowed us to identify the growth mode of Py and Co on Au as the island growth mode up to 0.35 and 0.24 nm, respectively.

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