Electronic Supplementary Material (ESI) for Nanoscale.

Supplementary Information

Field-Free switching of perpendicular magnetization through spin-orbit torque in FePt/[TiN/NiFe]$_5$ multilayers

Sun Chao[1, 2, 3], Jiao Yiyi[1, 2, 3], Chao Zuo [4]*, Hu Xin[1, 2, 3], Tao Ying[1, 2, 3], Fang Jin[1, 2, 3], Wenqin Mo[1, 2, 3], Yajuan Hui[1, 2, 3], Junlei Song[1, 2, 3], Dong Kaifeng[1, 2, 3]*

[1] School of Automation, China University of Geosciences, Wuhan 430074, China

[2] Hubei key Laboratory of Advanced Control and Intelligent Automation for Complex Systems, Wuhan 430074, China

[3] Engineering Research Center of Intelligent Technology for Geo-Exploration, Ministry of Education, Wuhan 430074, China

[4] Wuhan Second Ship Design and Research Institute, Wuhan 430064, China

I. The AHE, crystallographic structures and current induced switching loops of FePt/[TiN/NiFe]$_3$ multilayers

Similar to the stacks of FePt/[TiN/NiFe]$_5$ multilayers, XRD image (Fig.S1 b) shows only weak FePt (001) peaks for FePt/[TiN/NiFe]$_3$ RT, indicating poor (001) texture and chemical ordering. For FePt/[TiN/NiFe]$_3$ HT, the chemical ordering increases as well as chemical ordering. Moreover, epitaxial growth of TiN/NiFe on the FePt film is also observed for FePt/[TiN/NiFe]$_3$ HT. As for AHE results (Fig.S1 a), it also shows similarity for FePt/[TiN/NiFe]$_3$ as compared to FePt/[TiN/NiFe]$_5$ such as the weaker PMA of FePt/[TiN/NiFe]$_3$ RT. Moreover, Figure S1 c and d give the current induced switching loops of FePt/[TiN/NiFe]$_3$. All the results are almost consistent with FePt/[TiN/NiFe]$_5$ including the change of rotation direction of switching loops under different H_x. The main difference is switching polarity under H_x=0 Oe for FePt/[TiN/NiFe]$_3$ HT. This indicates different inherent H_{in}, which may be affected by the layer numbers of TiN/NiFe.

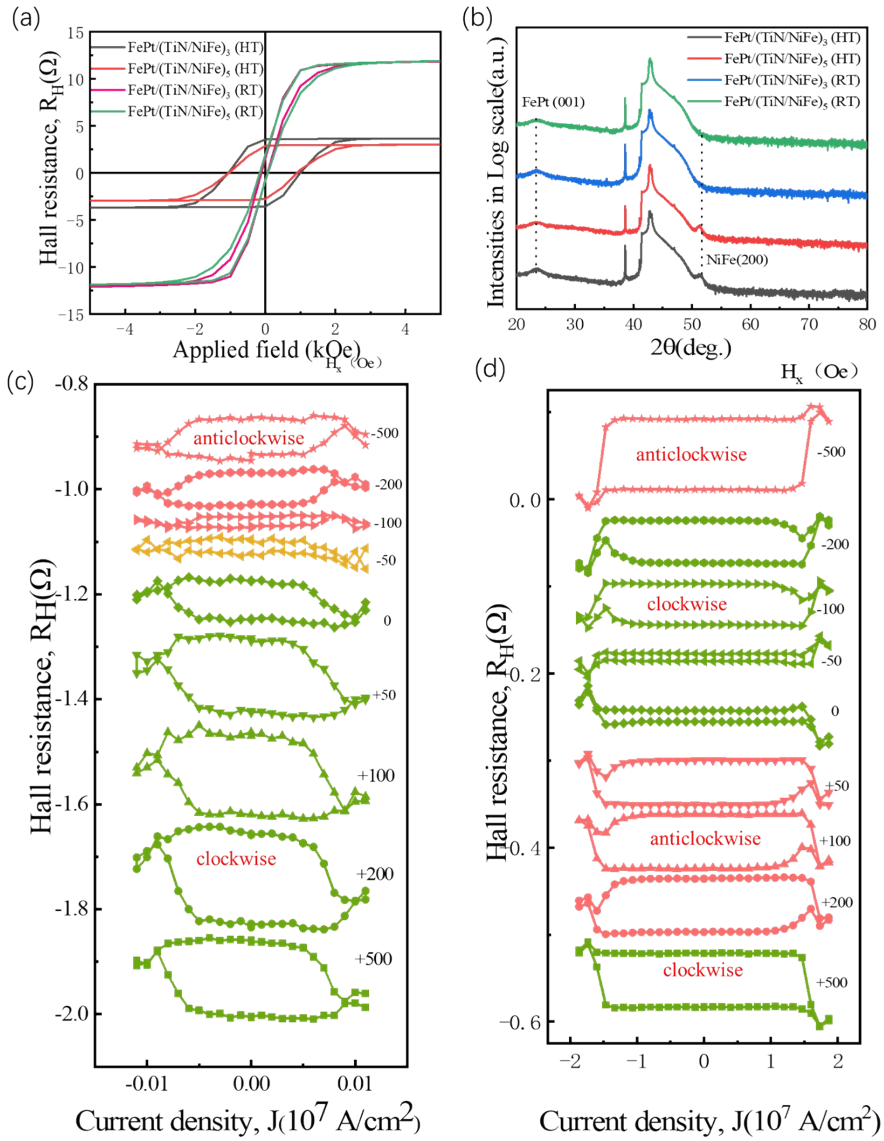

Figure S1 (a) AHE loops of FePt/[TiN/NiFe]$_n$ multilayers, (b) the corresponding XRD image of the FePt/[TiN/NiFe]$_5$ multilayers, (c) current-induced magnetization switching of FePt films with different external fields H_x of FePt/[TiN/NiFe]$_3$ RT (d) current-induced magnetization switching of FePt films with different external fields H_x of FePt/[TiN/NiFe]$_3$ HT

II. Investigations on IEC in FePt/[TiN/NiFe]$_n$

To scrupulously investigate the IEC in FePt/[TiN/NiFe]$_n$, we have studied the performance of FePt/TiN/NiFe trilayers, in which different thicknesses of TiN(0, 1, 2, 3nm) are used. The results are shown in Fig. S2. For devices with TiN 0 nm, no deterministic switching is observed at H_x=0 Oe and the switching behavior under different H_x is similar to the behavior of single FePt, indicating the inexistence of IEC (Fig. S2 c). While for the devices with TiN 1nm (Fig. S2 d), the field-free switching is realized and by varying external field (from 100 Oe to -100 Oe) the transition of switching polarity between clockwise and anticlockwise only happens for once. Such behavior is consistent with the ferromagnetic coupling in our model. As for the devices with TiN 2, 3nm (Fig. S2 e, f), the switching polarities change for three times with the H_x from 500 Oe(200 Oe) to -500 Oe (-200 Oe), which is similar to the behavior of FePt/[TiN/NiFe]$_5$ HT (sample 2 in main manuscript). This characteristic is agreement with the antiferromagnetic coupling. Those experiments prove that with varying the thickness of space layer the oscillation between ferromagnetic and antiferromagnetic coupling happens, which is a typical attribute of IEC.

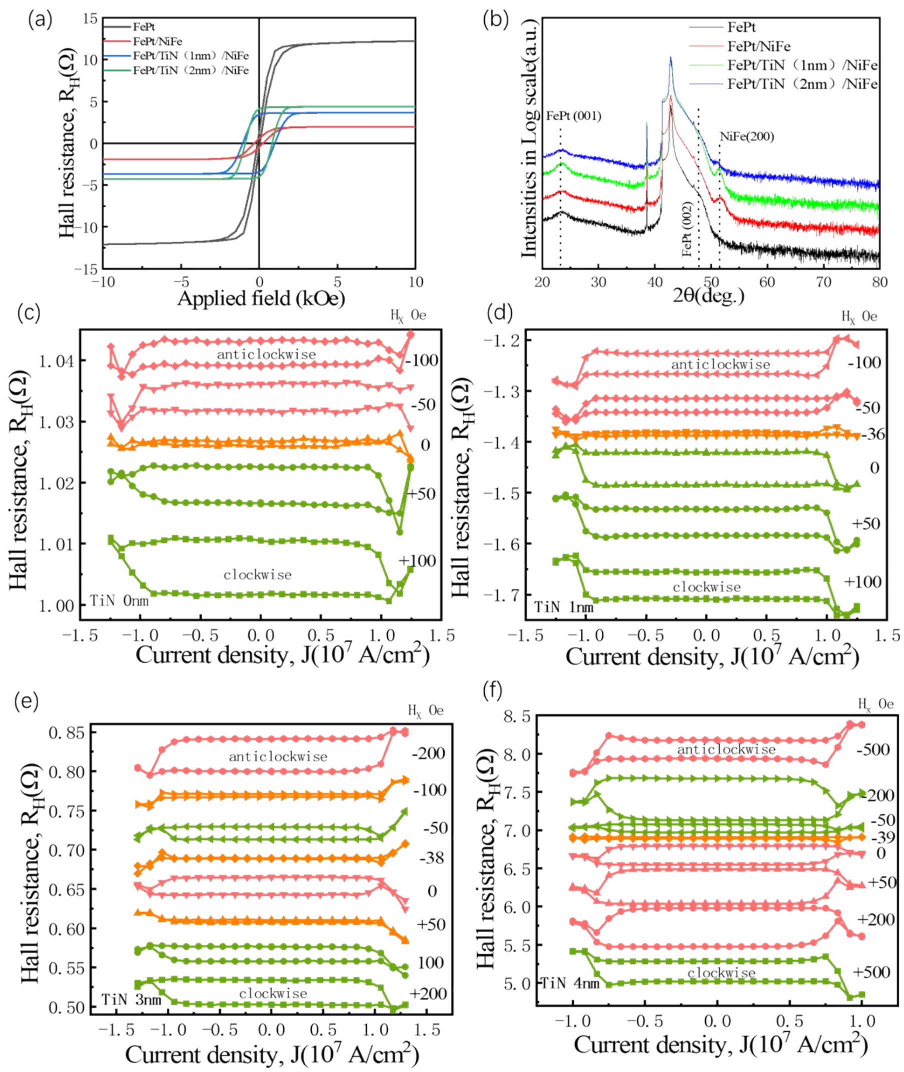

Figure S2 (a) the AHE loops for different structures, (b) the corresponding XRD results, the current induced magnetization switching for FePt under varying in-plane field H_x of samples with different TiN thickness (c) TiN 0nm, (d)TiN 1nm, (e) TiN 2nm, (f) TiN 3nm, respectively

Furthermore, we will discuss the IEC in FePt/[TiN/NiFe]$_n$. According to Bruno's study [1], the oscillations of IEC depend on both the thickness of space layer and ferromagnetic layer. As a result, the IEC between FePt and [TiN/NiFe]$_n$ is affected by the thickness of TiN and NiFe, the number of n and the IEC of NiFe/TiN/NiFe, which is a complex question. In order to simplify the effect of IEC on FePt SOT switching, in this paper, we mainly focus on the effect of the thickness of TiN and the number of n, and neglect the other factors.

Following this, Table 1 summaries the characteristics of IEC for different structures. In details, the thickness of TiN in main manuscript is that 1nm for sample 3 (FePt/[TiN/NiFe]$_5$ RT) and 2 nm for sample 2 (FePt/[TiN/NiFe]$_5$ HT) due to formation temperature. The results show that the thickness of TiN and n in [TiN/NiFe]$_n$ can affect the type of IEC and thus influence the critical values for transition of switching polarities.

Table 1 the comparison of IEC effects for different structures

Structure	*Type of IEC*	*Change times of switching polarities*	*Critical values for transition of switching polarities (Oe)*
FePt	~	1	0
FePt/NiFe	~	1	0
FePt/TiN(1nm)/NiFe	FM	1	-36
FePt/TiN(2nm)/NiFe	AFM	2	1st 50, 2st -38, 3st -100
FePt/TiN(3nm)/NiFe	AFM	3	1st 200~500, 2st -39, 3st -200~-500
FePt/[TiN(1nm)/NiFe]$_3$ HT	AFM	3	1st 200~500, 2st 0~50, 3st -200~-500
FePt/[TiN(2nm)/NiFe]$_3$ RT	FM	1	-50
FePt/[TiN(1nm)/NiFe]$_5$ HT	AFM	3	1st 200, 2st 0~-50, 3st -200~-500
FePt/[TiN(2nm)/NiFe]$_5$ RT	FM	1	-50

III. The possible source of H_{in}

We firstly check the FePt/TiN interface. As shown in Fig S3 a, there is no magnetization switching loops at H_x=0 Oe, indicating the FePt/TiN interface are not responsible for such inherent field. Then, the magnetic properties of FePt film are studied. Two FePt samples with different deposition temperature (300°C or 500°C) are prepared and Fig. S3 d shows their AHE loops, which indicating the coercivity of 500°C deposited FePt is much larger than that of 300°C deposited sample. Following this, the two FePt/TiN/NiFe samples are fabricated, during this process the sputtering conditions for TiN and

NiFe layer keep the same. AHE results (Fig. S3 e) show that the sample with 500℃ FePt still has larger coercivity, while coercivity of the sample with 300℃ FePt is close to the value of FePt/[TiN/NiFe]$_5$ HT (sample 2 in main manuscript). Fig. S3 b shows the switching loops for the sample with 500℃ FePt/TiN(2nm)/NiFe. By changing the direction of NiFe film, the switching polarity of FePt film is changeable at H_x=0 Oe. Such characteristics is a typical anti-ferromagnetic coupling and there is no inherent field. On the contrary, the inherent field appears in sample with 300℃ FePt (Fig. S3 c). Thus, we infer the source of inherent field is associated with the magnetic properties of FePt film and may originate from the complex coupling in FePt/TiN/NiFe system, which needs further investigation.

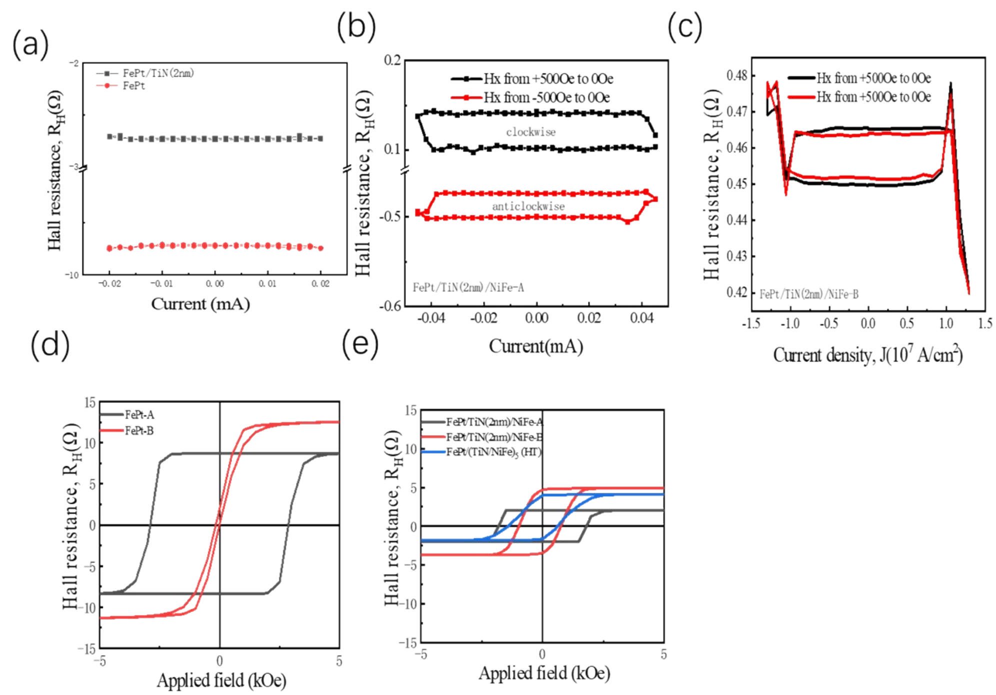

Figure S3 current-induced magnetization switching of FePt films at H_x= 0 Oe of (a) FePt and FePt/TiN bilayers; the switching loops under H_x=0 Oe after using an in-plane 500 Oe or -500 Oe fields to saturate NiFe for (b) FePt/TiN(2nm)/NiFe-A, in which FePt is deposited at 500℃, (c) FePt/TiN(2nm)/NiFe-B, in which FePt is deposited at 300℃; (d) AHE loops for FePt with different deposition temperature, FePt-A 500℃, FePt-B 300℃; (e) AHE loops for different samples

IV. The switching models for sample 2 and sample 3

The change of H_E relates to the remanent magnetization of NiFe layer. With varying the external field H_x, the changeable remanent magnetization of NiFe may result in the variable H_E, which exists both in sample 2 and 3. However, the coupling type is different, that is antiferromagnetic coupling for sample 2 and ferromagnetic coupling for sample 3. For antiferromagnetic coupling, the effective field

H_E performs opposite direction compared to the magnetic direction of NiFe layer, while the direction of H_E is the same as the direction of NiFe for ferromagnetic coupling. As a result, the different directions of H_E combined with H_{in} and external field H_x cause the different switching characteristics for sample 2 and 3.

In details, with varying H_x from -500 Oe to 500 Oe the switching processes for sample 2 are shown in Fig. S4. When H_x is smaller than -50 Oe, the large remanent magnetization of NiFe induces the maximum H_{Emax} (corresponding to A to C sites). In those sites, the H_x and H_{in} have the same direction, which is opposite to H_{Emax}. Decreasing $|H_X|$, the relationship between $|H_X| + |H_{in}|$ and $|H_{Emax}|$ varies and switching direction changes for once. At site D (H_x between -50 Oe to 0 Oe), the decreasing remanent magnetization of NiFe causes the decreased H_{Emin1} and the $|H_X| + |H_{in}| = |H_{Emin1}|$ determines the disappearance of switching loop. When H_x is equal to 0 Oe (site E), the further decreased remanent magnetization results in smaller H_{Emin0} and the field-free switching is obtained due to $|H_{in}| > |H_{Emin0}|$. Between D and E site, the second change for switching direction happens. On the contrary, when varying H_x from 50 Oe to 500 Oe, the magnetization of NiFe changes the direction. The H_{-E} and H_{in} have the same direction, opposite to H_{-X}. Similarly, the relationship between $|H_{-Emax}| + |H_{in}|$ and $|H_{-X}|$ varies due to changeable $|H_{-X}|$and the third change for switching direction is observed.

As for sample 3, the switching processes are shown in Fig. S5, under H_x from -500 Oe to 500 Oe. When H_x is smaller than -100 Oe, H_x and H_E have the same direction, opposite to H_{in}. The sum of $|H_X| + |H_{Emax}|$ is always larger than $|H_{in}|$ and the switching direction keeps unchangeable. Decreasing H_x to -50 Oe (site B), the smaller remanent magnetization of NiFe corresponds to smaller H_{Emin1} and $|H_X| + |H_{Emin1}| = |H_{in}|$ determines the disappearance of switching loop. When H_x is equal to 0 Oe (site C), the field-free switching is obtained due to $|H_{in}| > |H_{Emin0}|$. For H_x varying from 50 Oe to 500 Oe, the magnetic direction of NiFe changes and H_{-E}, H_{-X}, H_{in} have the same direction. In this case, no matter how H_E changes with respect to remanent magnetization of NiFe the switching polarities always keep the same. As a result, the change for switching directions can be only observed for once.

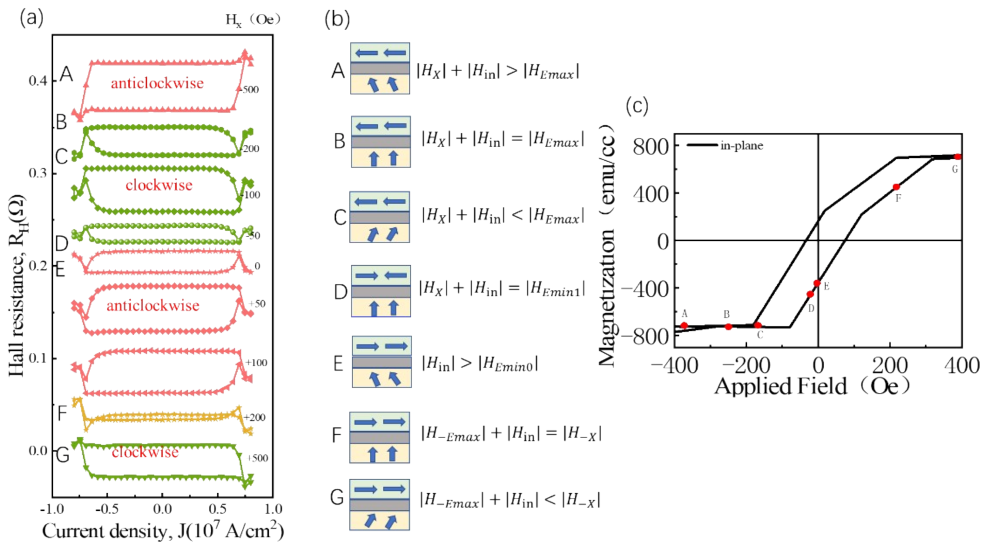

Figure S4 (a) current-induced magnetization switching of FePt films with different external fields H_x of sample 2, (b) the corresponding model of switching process with different H_x, (c) the remanent magnetization states of NiFe with different H_x

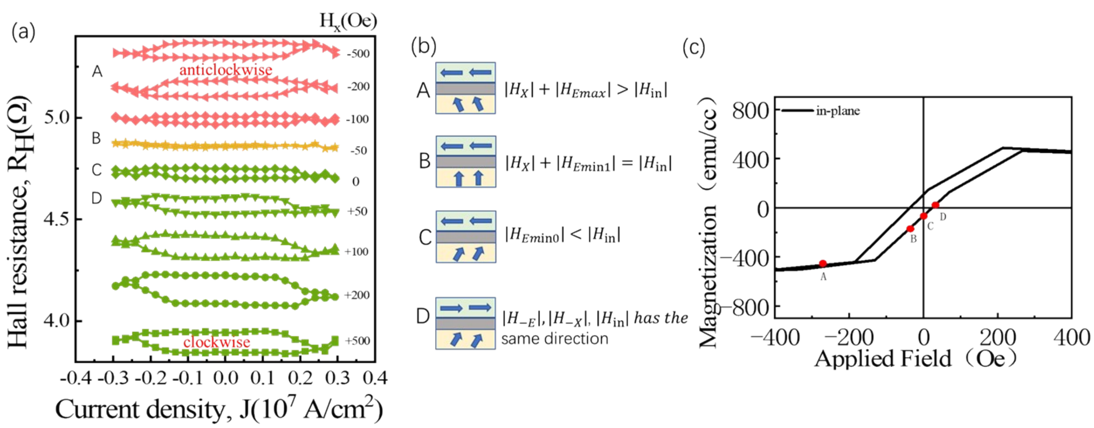

Figure S5 (a) current-induced magnetization switching of FePt films with different external fields H_x of sample 3, (b) the corresponding model of switching process with different H_x, (c) the remanent magnetization states of NiFe with different H_x

V. The memristive behavior of sample 2 with increasing counts of positive pulses from 20 to 80

A series of current pulses are applied with varying counts of positive pulses from 20 to 80, and similarly R_H varies gradually with the increasing pulses numbers, as shown in Fig. S6. Such a stably memristive characteristics of our devices shows good application as a synapse in a self-adaptive network.

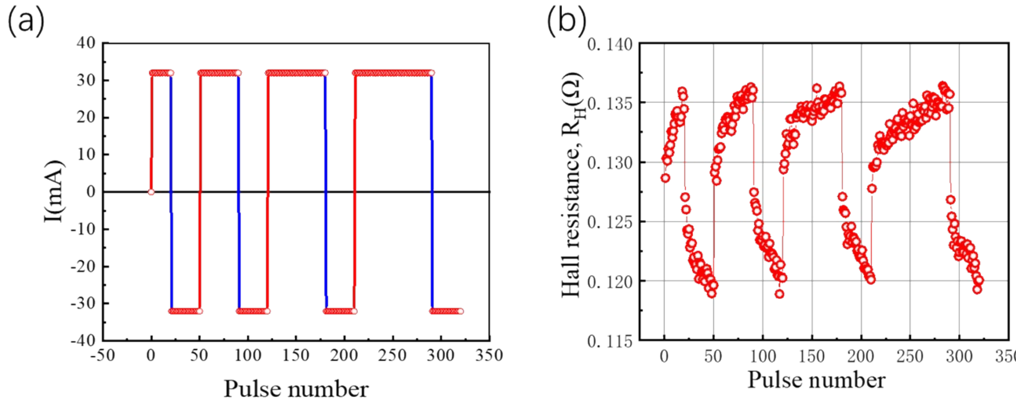

Figure S6 (a) the applied train of current pulses with H_x=200 Oe, (b) the corresponding response of R_H

REFERENCES

[1] P. Bruno, Oscillations of interlayer exchange coupling *vs.* ferromagnetic-layers thickness, *EPL*, **1993**, 23: 615.