Journal of Magnetics 10(2), 44-47 (2005)

Pt Thickness Dependence of Oscillatory Interlayer Exchange Coupling in [CoFe/Pt/CoFe]/IrMn Multilayers with Perpendicular Anisotropy

Sang-Suk Lee[1,2]*, Jong-Gu Choi[2], Sun-Wook Kim[3], Do-Guwn Hwang[1,2] and Jang-Roh Rhee[4]

[1]*Department of Computer and Electronic Physics, Sangji University, Wonju 220-702, Korea*
[2]*Department of Functional Electron and Materials, Graduation, Sangji University, Wonju 220-702, Korea*
[3]*Life Science Institute, Sangji University, Wonju 220-702, Korea*
[4]*Department of Physics, Sookmyung Women's University, Seoul 140-742, Korea*

(Received 19 May 2005)

The oscillatory interlayer exchange coupling (IEC) has been shown in pinned [CoFe/Pt(t_{Pt})/CoFe]/IrMn multilayers with perpendicular anisotropy. The period of oscillation corresponds to about 2 monolayers of Pt. The oscillatory behavior of IEC depending on the nonmagnetic metallic Pt thickness is thought to be related the antiferromagnetic ordering induced by IrMn layer. Oscillatory IEC as function of insulating NiO thickness has been observed in [Pt/CoFe]$_4$/NiO(t_{NiO})/[CoFe/Pt]$_4$ multilayers. The effect of N (number of bilayer repeats) upon the magnetic property of [Pt/CoFe]$_N$/IrMn is also studied.

Key words : interlayer exchange coupling (IEC), perpendicular anisotropy, nonmagnetic metallic Pt layer, antiferromagnetic IrMn layer

1. Introduction

The oscillatory interlayer exchange coupling (IEC) between the ferromagnetic (FM) layers separated by nonmagnetic metallic spacers with in-plane magnetic anisotropy appears in the multilayer structures with out-of-plane one such as Co/Ru and Ni/Cu superlattices and with in-plane one such as Fe/Cr/Fe sandwiches, respectively [1-3]. Although nonoscillatory decay of the IEC strength with insulating thickness has been observed, an existence of oscillatory IEC in [Pt/Co]$_3$/NiO/[Co/Pt]$_3$ multilayers with perpendicular anisotropy already has reported by Z. Y. Liu *et al.* [4]. Their results were explained that the insulating NiO spacer is modeled by a rectangular potential barrier height of U_0 higher than the Fermi level E_F of the FM layers, and the IEC is ascribed to the interference of electron waves in the spacer layer due to spin-dependent reflections at the FM/insulator interfaces. However, a study on the oscillatory IEC in the pinned out-of-plane magnetic multilayers using the antiferromagnet (AF) layer has not been reported.

In this letter, we demonstrate the oscillatory IEC as a function of the Pt thickness in $Co_{90}Fe_{10}$(1.0 nm)/Pt(t_{Pt})/$Co_{90}Fe_{10}$(1.0 nm)/$Ir_{22}Mn_{78}$(10 nm) multilayers with in an out-of-plane easy axis. The effect of N upon the magnetic property of [Pt/CoFe]$_N$/IrMn is investigated. In addition, we report that the oscillatory IEC as function of NiO thickness has been observed in [Pt/CoFe]$_4$/NiO(t_{NiO})/[CoFe/Pt]$_4$ multilayers with perpendicular anisotropy.

2. Experimentals

The [Buffer: NiO(2 nm)/Pt(0.8 nm) or Pt(10 nm)]/CoFe (1.0 nm)/Pt(0.8 nm)/CoFe(1.0 nm)/IrMn(10 nm) multilayers were deposited by dc and rf magnetron sputtering at room temperature (RT) on glass (Corning 7059) in a vacuum system with a base pressure of 1×10^{-6} Torr and working pressure of $3\sim5 \times 10^{-3}$ Torr. Because the buffer layer is important to got the initial growth and smooth surface roughness of [CoFe/Pt] multilayers, it grown on glass substrate at RT with optimal layer thickness. The deposition rates of the separated Pt, CoFe, IrMn, and NiO targets were of 0.21, 0.22, 0.13, and 0.02 nm/s, respectively. During deposition the NiO layer, the growth pressure was prepared at only Ar gas partial pressure of 3×10^{-3} Torr without the introducing oxygen gas (O_2). The interval of each layer sequence in multilayer film

---

*Corresponding author: Tel: +82-33-730-0415,
e-mail: sslee@sangji.ac.kr

structure during the deposition was maintained within 0.5 s. Where the number of repeats (N) of [Pt/CoFe]$_N$ is increased to 5. The thickness calibration was checked by grazing angle x-ray reflectivity after sample preparation, displaying an accuracy of 10% and a roughness of 0.2-0.3 nm. Hysteresis loops of as-prepared samples obtained by the extraordinary Hall voltage amplitude (EHA) curves, with magnetic field applied perpendicular to the film direction [5]. Magnetic property of all samples was confirmed by surface magneto-optical Kerr effect (SMOKE) and a superconducting-quantum-interference-device (SQUID) magnetometer.

3. Results and Discussions

The x-ray diffraction (XRD) patterns of Buffer/[CoFe (1.0 nm)/Pt(0.8 nm)]$_5$ multilayers reveal a Pt(111) peak. The crystalline Pt(111) peak was reduced as increasing the CoFe thickness. As total thickness of the buffer NiO/Pt bilayers or Pt layer was changed from 0 to 10 nm, the peaks of NiO(111) or Pt(111) intensity were almost the same amplitudes. No peaks corresponding to other crystallographic orientations are observed. The pinned effect by buffer [NiO(3 nm)/Pt(0.8 nm)] bilayers does not arise from the exchange biasing (EB) due to the NiO layer, because the exchange biasing for a thin NiO layer within 3 nm and above Pt layer disappears completely at RT and the exchange biasing between FM (CoFe) and AF (NiO) layers is nothing at Pt contaminated interface. The EHA curves agreed with the values (coercive fields) measured by a SMOKE. Both EHA and SMOKE curves are fairly square, implying out-of-plane easy axes. The hysteresis loops obtained from the EHA curve for samples without AF IrMn layer do not display any shift at RT.

Fig. 1(a) and (b) show the comparison curves of SQUID and Hall voltage for the glass/Buffer/[CoFe(1.0 nm)/Pt(0.8 nm)/CoFe(1.0 nm)]/IrMn(10 nm) multilayers with out-of-plane magnetic anisotropy, which were measured at RT, respectively. From two curves, we confirmed that the measured M-H loops by the different methods show the same coercive field of $H_c = 615$ Oe and two exchange biased fields of $H_{ex} = 470$ Oe, respectively. Here the H_{ex} is determined by a center value of one shift major loop in EHA curve. It is proven that the M-H loop measured by EHA curve for magnetic films with perpendicular anisotropy is easy and clear. Fig. 1(c) shows the magnetic domain image observed by the magnetic force microscopy (MFM) at one upper remanent state ($H = 0$ Oe). The used method of MFM (Digital Instruments, Nanoscope IIIa) was a tapping mode. The scan area is 8 μm × 8 μm for the [CoFe(1.0 nm)/Pt(0.8 nm)/CoFe(1.0 nm)]/IrMn(10 nm) multilayers with out-of-plane magnetic anisotropy. Here, relatively irregular magnetic domain walls with wide line patterns demonstrate the existence of multiple domain walls different to those observed in AF coupling [Pt/Co]$_3$/NiO/[Co/Pt]$_3$ and Co/Ru/Co multilayers [4, 6]. For the [Co/Ru] multilayer, the narrow strip width is somewhat distributed around the averaged value of 80 nm. Note that some bubble domains coexist with interconnected strip patterns [7]. This phenomenon will be related to the larger shape anisotropy energy [8] (equivalently, the magnetostatic energy) of [Co/Ru] multilayer than one of [CoFe/Pt] multilayer.

Fig. 2 shows the EHA curves of Buffer/[Pt(0.8 nm)/CoFe(1.0 nm)]$_N$/IrMn(10 nm) multilayers with the number ($N = 2$, 3, 4, and 5) of [Pt/CoFe] bilayer repeats. As N decreases down to 2, the perpendicular exchange biased field (H_{ex}) of the nearest CoFe/IrMn bilayer increases 170 Oe to 350 Oe. The Hall voltage magnitude for the bottom

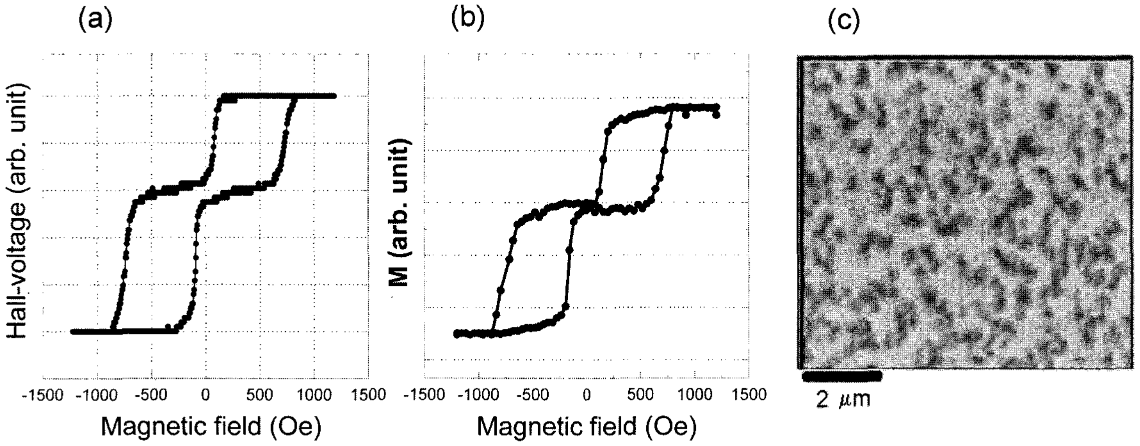

Fig. 1. (a) The Hall-voltage curve and (b) SQUID curve along the out-of-plane easy axis for the glass/Buffer/[CoFe(1.0 nm)/Pt(0.8 nm/CoFe(1.0 nm)]/IrMn(10 nm) multilayers. (c) The magnetic force image at the upper remnanent (H = 0 Oe).

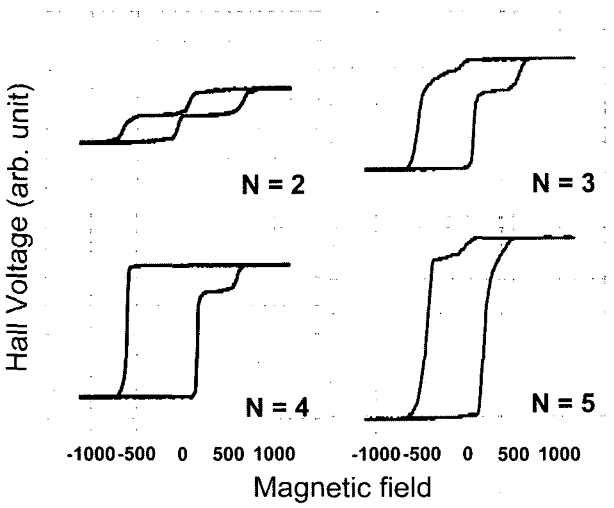

Fig. 2. The major extraordinary Hall-voltage amplitude (EHA) curves along the out-of-plane easy axis for glass/Buffer/[Pt(0.8 nm)/CoFe (1.0 nm)]$_N$/IrMn(10 nm) (N = 2, 3, 4, 5).

[CoFe(1.0 nm)/Pt(0.8 nm)]$_{N-1}$ is proportional to the number of [CoFe/Pt] bilayers. On other side, the one for the exchange biased upper [CoFe/Pt] with AF IrMn layer is almost same. However, the H_{ex}s of [Pt/CoFe]$_N$/IrMn multilayers are symmetrically shift due to IEC between [CoFe/Pt]$_{N-1}$ multilayers and [CoFe/IrMn] bilayer. In case of even N = 2 and 4, the perpendicular exchange bias in multilayers induced by CoFe/IrMn bilayer is larger than one in case of odd N = 3 and 5. The existence for asymmetric hysteresis curves, in case of N = 4 and 5, is due to the relative strengths of pinning CoFe/IrMn and the ferromagnetic coupling between the CoFe layers with three and four [CoFe/Pt] bilayers. It has been shown that it is possible to control exchange bias in compensated multilayer exhibiting a perpendicular-to-film magnetic anisotropy. Especially, the IEC as a function of Pt thickness in [CoFe(1.0 nm)/Pt(t_{Pt})/CoFe(1.0 nm)]/IrMn(10 nm) multilayers will be discussed later.

Fig. 3 shows an normalized Hall-voltage curves as a function of NiO thickness at RT for the glass/[Pt(0.8 nm) /CoFe(1.0 nm)]$_4$/NiO(t_{NiO})/[CoFe(1.0 nm)/Pt(0.8 nm)]$_4$ multilayers. Here the NiO thickness was above 0.5 nm. The bold line and thickness values show a period of two monolayers of NiO. That is, it shows clearly that at RT the IEC oscillates between AF and ferromagnetic (FM) coupling as a function of NiO thickness with a period of ~0.5 nm [9]. From our above result, we confirmed the experimental results of Z. Y. Liu group [4], in which they reported that the unexpected oscillatory behavior is quite different from the non-oscillatory decay of IEC strength expected by the models of Bruno [2, 10] and Slonczewski [11] for nonmagnetic insulating spacers and from recent experimental observations of coupling across a nonmagnetic insulating MgO spacer [4, 10]. Also, we found the similar results that a coexistence of exchange biasing and AF interlayer exchange coupling has been observed after cooling the sample to 77 K at zero field.

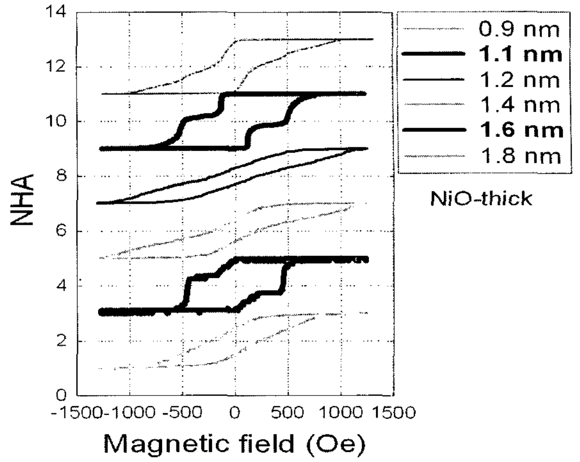

Fig. 3. Normalized Hall-voltage curves as a function of NiO thickness at room temperature. for the glass/[Pt (0.8 nm)/ CoFe(1.0 nm)]$_4$/NiO(t_{NiO})/[CoFe (1.0 nm)/Pt(0.8 nm)]$_4$ multilayers. The bold lines and thickness values show a period of two monolayers of NiO.

Fig. 4 shows that the oscillatory phenomenon of interlayer exchange coupling field (H_{IEC}) can be unambiguously attributed only to IEC between the two FM layers across the thin Pt spacer. The multilayer structure is [CoFe(1.0 nm)/Pt(t_{Pt})/CoFe(1.0 nm)]/IrMn(10 nm). Where

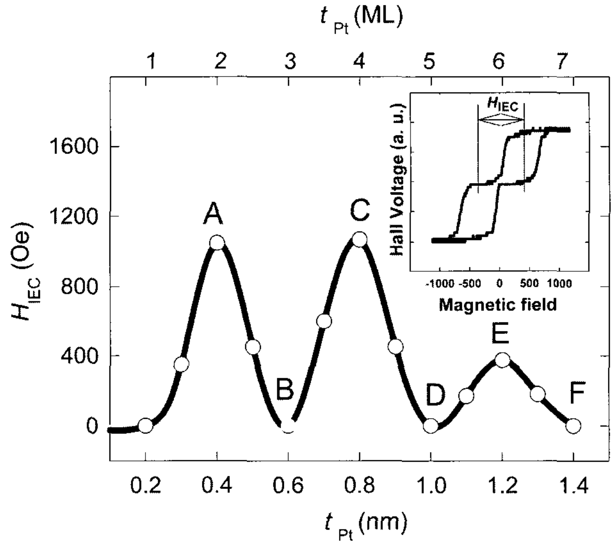

Fig. 4. The H_{IEC} strength as a function of Pt thickness (in units of both nm and ML) for glass/Buffer/CoFe(1.0 nm)/Pt(t_{Pt})/ CoFe(1.0 nm)/IrMn(10 nm). H_{IEC} is defined by interval value between two exchange biasing fields of minor loops in inset.

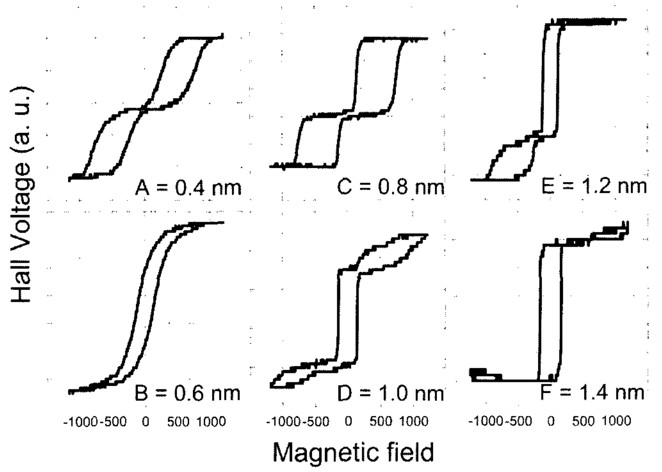

Fig. 5. The major anomalous Hall-voltage curves along the out-of-plane easy axis for glass/Buffer/CoFe(1.0 m)/Pt(t_{Pt})-CoFe(1.0 nm)/IrMn(t_{Pt} = 0.4, 0.8, and 1.2 nm vs t_{Pt} = 0.6, 1.0, and 1.4 nm).

H_{IEC} is defined by interval value between two exchanges biasing fields of minor hysteresis loops, as shown in inset. The characteristics of periodic t_{Pt} in the Pt thickness with a period of 2d 0.4 nm [where d = 1.96 nm is the distance between (111) planes] is similar to the results of the out-of-phase magnetization for the AF ordering of insulating spacer and the in-plane model for the metallic spacer by Z. Y. Liu *et al.* and Bruno *et al.*, respectively [4, 6]. Therefore, the oscillatory behavior of IEC depending on the nonmagnetic metallic Pt thickness is thought to be related the AF ordering induced by AF IrMn layer. However, in-plane magnetic shape anisotropy, this result is different from the typical feature that the coupling observed in AF coupling media is thought to originate predominantly from the Ruderman-Kettel-Kasuya-Yoshida (RKKY)-type coupling [12] typically found in Co/Ru/Co multilayers with period of long range about 1.1 nm as t_{Ru} changes, with the coupling strength decreasing $1/t_{Ru}$ [6].

The major EHA and magnetization versus out-of-plane magnetic field curves are shown in Fig. 5 for six [CoFe/Pt/CoFe]/IrMn multilayers structure containing 1.0 nm CoFe layer and Pt layer thickness ranging from 0.4 nm to 1.4 nm, as shown in Fig. 4. Fig. 5 shows the detailed dependence of the saturation EHA and the saturation field on the thickness of Pt layer. For t_{Pt} = 0.4 nm and 0.8 nm, the field dependence of EHA and magnetization are similar to that for comparable $[Pt/Co]_3/NiO/[Co/Pt]_3$ structure [4], but the magnitude of H_{IEC} is much smaller than it. H_{IEC}s increase as t_{Pt} approach to 0.4 nm and 0.8 nm, attaining values of about 1 kOe for t_{Pt} = 0.4 nm or 0.8 nm approximately 2 monolayers. As t_{Pt} is increased beyond 1.2 nm H_{IEC} decrease to half value for tPt in 0.8 nm. In case of t_{Pt} = 0.6, 1.0, and 1.4 nm, the H_{IEC}s obtained from the EHA curves are almost zero. Therefore, these results show that the oscillation dependence of IEC for the [CoFe/Pt/CoFe] multilayer system induced by IrMn with spacer-layer thickness is a important features of perpendicular exchange biased system.

4. Conclusions

We have observed oscillations, as a function of spacer-Pt layer thickness, in the amplitude of IEC in pinned [CoFe/Pt/CoFe]/IrMn multilayers with perpendicular anisotropy. The period of the oscillation is about 2 monolayers 0.4 nm. The newly discovered [CoFe/Pt/CoFe]/IrMn system is particularly interesting in that the spacer Pt is nonmagnetic metal layer. The oscillatory behavior of IEC as a function of the Pt layer is thought to be related the AF ordering induced by IrMn layer. The oscillatory IEC as function of NiO thickness has been observed in $[Pt/CoFe]_4/NiO(t_{NiO})/[CoFe/Pt]_4$ multilayers and proved Z. Y. Liu group's results. The effect of N (CoFe/Pt bilayer repeats) upon the magnetic property of $[Pt/CoFe]_N/IrMn$ is also studied.

Acknowledgements

One of the authors (S. S. Lee) would like to thank B. H. Seung (POSTECH) for help with SQUID measurement. This work was supported by Korea Research Foundation Grant (KRF-2004-041-D00316).

References

[1] P. Grunberg *et al.*, Phys. Rev. Lett. **57**, 2442 (1986).
[2] P. Bruno, and Chappert, Phys. Rev. Lett. **67**, 1602 (1991).
[3] M. D. Stiles, Phys. Rev. **B 48**, 7238 (1993).
[4] Z. Y. Liu and S. Adenwalla, Phys. Rev. Lett. **91**, 37207 (2003).
[5] H. W. Joo *et al.*, J. of Magnetics **10**(1), 33 (2005).
[6] D. T. Margulies *et al.*, Appl. Phys. Lett. **80**, 91 (2002).
[7] S. Hamada *et al.*, J. Magn. Magn. Mater. **240**, 539 (2002).
[8] D. G. Hwang *et al.*, J. of Magnetics **7**(3), 94 (2002).
[9] S. S. Lee *et al.*, Phys. stat. sol. (c) **1**(12), 3360-3562 (2004).
[10] P. Bruno, Phys. Rev. **B 52**, 411 (1995).
[11] J C. Slonczewski, Phys. Rev. **B 39**, 6995 (1989).
[12] S. S. P. Parkin *et al.*, Phys. Rev. Lett. **64**, 2304 (1990).