Article

Perpendicular exchange bias of Co/Ni multilayers adjacent to antiferromagnetic FeRh Layer

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Abstract: The perpendicular exchange bias effect is observed in the ferromagnetic Co/Ni multilayers adjacent to the antiferromagnetic FeRh layer. It is found that as the antiferromagnetic FeRh thickness increases from 10 Å to 50 Å, the hysteresis loop is gradually changed from the symmetric shape to the asymmetric shape shifted by some amount corresponding to the exchange-biased field at the thickness of 25 Å. Also, the magnetic domain observation experiment confirms that the domain reversals in the increasing and the decreasing field regions of the sample with the thickness of 50 Å exhibit the same single domain wall motion even though they have the different coercivities.

Keywords: exchange bias effect, perpendicular exchange bias

1. Introduction

In general, when the ferromagnetic (FM) film is adjacent to the antiferromagnetic (AFM) layer, the magnetic hysteresis loop of the film exhibits an asymmetric shape moved to a particular direction of magnetic field due to the interaction at the interface[1]. Such phenomena in the AFM/FM film is called as an exchange bias effect. In addition, the magnetic hysteresis loop shifted to a certain direction is used to measure the degree of the exchange bias effect. While the exchange bias effect is classified as an in-plane exchange bias and a perpendicular exchange bias depending on the magnetic anisotropy direction of the FM film, most studies have been done in the in-plane exchange bias so far[2–8]. However, since the perpendicular exchange bias is recently discovered, new phenomenon in the promising exchange bias have attracted new attention due to the possibility of application to spintronics devices such as magnetic sensors, magnetic recording read heads and magnetic random access memory (MRAM)[9–15].

In most FM/AFM structures with perpendicular exchange bias effect, Co/Pd[16–18] and Co/Pt[9–11,15] mulilayers have being mainly used for the FM material due to their strong perpendicular magnetic anisotropy, while FeRh[19–21], FeMn[11,22], IrMn[9,15,23,24], and $FeCl_2$[25] are considered as the AFM material. Furthermore, since the asymmetric inversion on magnetization is observed in the perpendicular exchange bias, the magnetic domain movement also have been actively studied to a broaden understanding of the exchange bias[13,26,27]. In particular, the change of the exchange bias magnetic field H_E and the coercivity H_C is known as the results of the complex interaction of AFM/FM domain wall as well as an unidirectional anisotropy coming from the AFM/FM interface[1,2,28,29].

In this paper, we confirmed the perpendicular exchange bias effect experimentally in a thin film composed of FM Co/Ni multilayer and AFM FeRh layer. In recent years, Co/Ni multilayer is being used for the current-induced spin dynamics due to its relatively small H_C and fast domain wall mobility compared to Co/Pd and Co/Pt multilayers[30–39]. In order to investigate the thickness of

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AFM layer dependent exchange bias effect, we produced samples with various thickness (from 10 Å to 50 Å) of FeRh which is G-type AFM material. G-type AFM material is a promising candidate to tailor the interface spin configuration for exchange bias. In G-type AFM materials, the nearest neighboring magnetic moments on the (001) plane align antiferromagnetically whereas those on the (111) plane have a ferromagnetically ordered spin configuration, providing the ideal uncompensated interface for exchange bias[40]. The magnetic hysteresis loops were measured by using a home-built longitudinal magneto-optical Kerr effect (MOKE) set-up based on photoelastic modulation. In addition, the magnetic domain revolution patterns in regions with both increasing and decreasing magnetic field were observed by using a magneto-optical microscope.

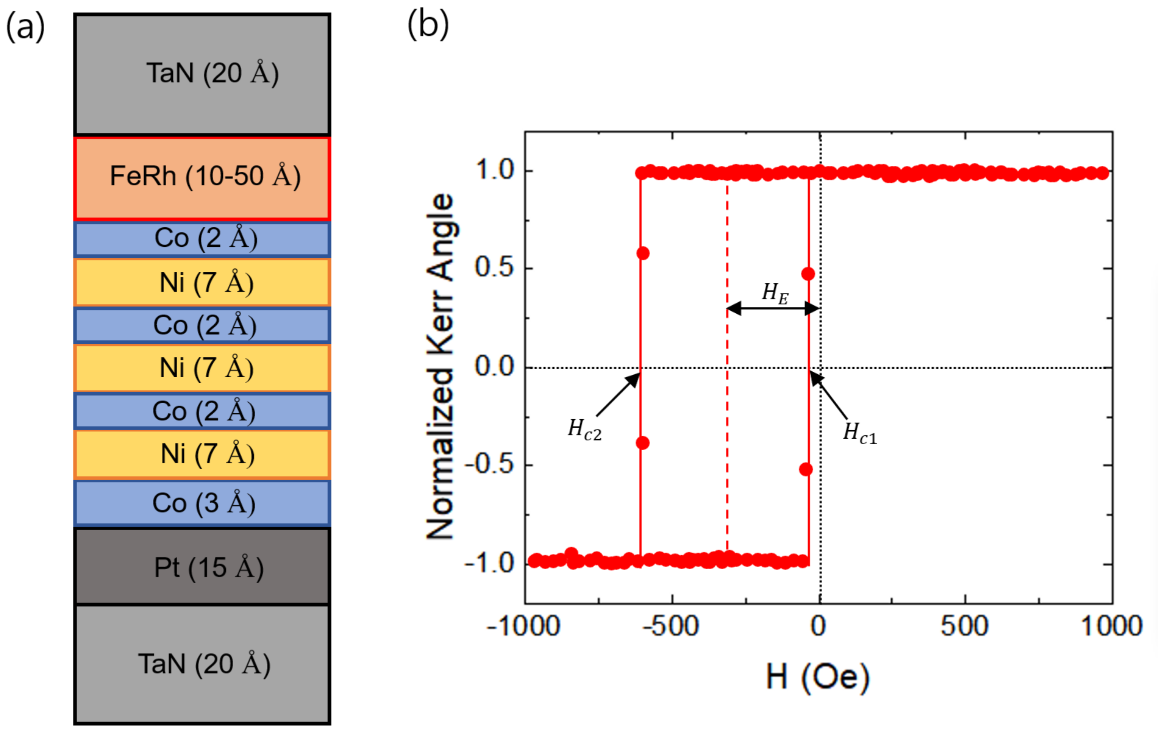

Figure 1. (a) Schematic diagram of the detailed sample structure basically consisting of the FM Co/Ni multilayer and the AFM FeRh layer. (b) Kerr hysteresis loop of the sample with the FeRh thickness of 50 Å exhibiting the exchange bias effect. Here, H_{C1} and H_{C2} correspond to the coercivities in the increasing and the decreasing field regions, respectively. H_E denotes the exchange-biased field.

2. Materials and Methods

The samples were deposited on the Si(100) substrate by using a dc magnetron sputtering system under working pressure of 1.4×10^{-6} Torr. The Si(100) substrates were loaded for deposition without removing the amorphous SiO_2, and the targets were pre-sputtered for 20 minute before deposition. A dc-magnetic field of 1.5 kOe was applied parallel to the substrate surface during the growth of the film to set the exchange bias direction in the films. All the layers were deposited at room temperature. During magnetic annealing was carried out in a vacuum chamber in 5×10^6 Torr at 400 °C for 1 hour, the annealing temperature was controlled using a proportional-integral-derivative (PID) controller.

The detailed structure of sample is illustrated in Fig. 1(a). In the exchange bias, Co/Ni multilayer with Pt contributes to the perpendicular magnetic anisotropy, while FeRh serves as AFM material. TaN deposited above and below the layer was used for the capping layer.

The measurements of the magnetic hysteresis loops were carried out using a home-built longitudinal MOKE. A solenoid was used to generate the magnetic field in steps of 0.3 Oe by sweeping the current using a programmable constant current source. The thickness of the individual layers was

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determined using specular X-ray reflectivity measurements carried out using X-pert Panalytical X-ray diffractometer. In addition, the magnetic domain revolution patterns under the increasing and the decreasing magnetic field were observed by using a magneto-optical microscope. The obtained image was converted to an artificial image with better contrast through a real-time image processing system.

3. Results and Discussion

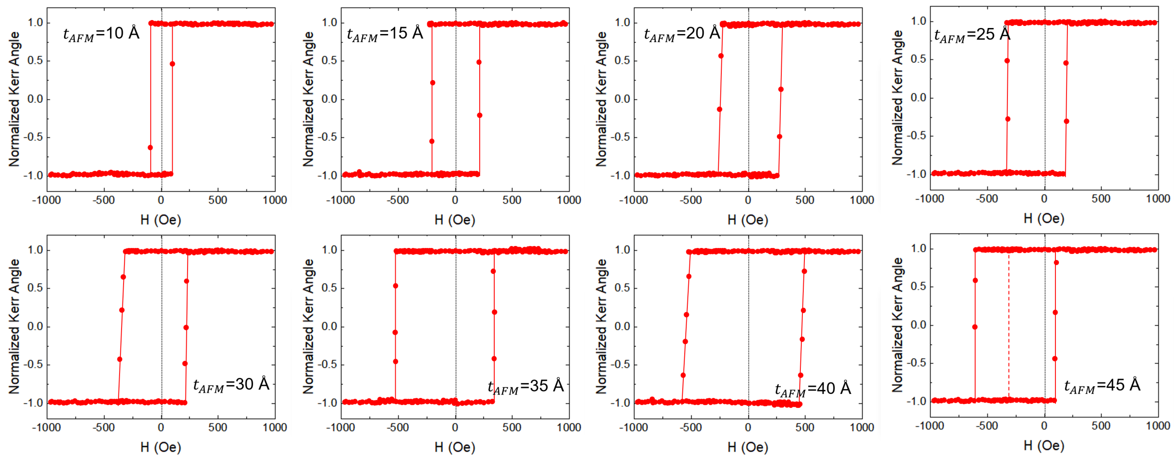

Figure 2. Various Kerr hysteresis loops of the samples with the FeRh thicknesses varying from 10 Å to 45 Å.

Using a longitudinal MOKE, we measured the magnetic hysteresis loop of the FM Co/Ni multilayer adjacent to the AFM FeRh layer of various thicknesses. Fig. 1(b) shows a magnetic hysteresis loop of a sample having a FeRh thickness t_{AFM}=50 Å. The Kerr angle corresponding to the magneto-optical intensity is almost proportional to the magnetization M of the magnetic material. Therefore, we present normalized Kerr angle (θ/θ_S) which corresponds to saturated magnetization (M_S) with angle of Kerr θ for convenience. Unlike a typical ferromagnetic thin film which shows a symmetrically shaped magnetic hysteresis loop, it exhibits an asymmetric shape moved from the origin. This is due to an unidirectional-anisotropy perpendicular to the sample created by the exchange interaction between the FM Co/Ni multilayer and the AFM FeRh layer at the interface. Such unidirectional-anisotropy shows different coercivity depending on the direction of the magnetic field in the magnetic hysteresis loop, as shown in Fig. 1(b). In order to investigate the magnetic properties of the AFM/FM film indicating the exchange interaction, the magnetic coercivity H_C and the exchange bias field H_E should be measured. In particular, the H_E is an important value to predict the degree of exchange interaction between FM and AFM layers. For the Co/Ni multilayer with 50 Å FeRh, H_C and H_E were measured as 225±5 and 325±5 Oe, respectively. These values were calculated from relations of H_C=(H_{C1}-H_{C2})/2 and H_E=-(H_{C1}+H_{C2})/2. Here, H_{C1} and H_{C2} are the values obtained under the increasing and the decreasing magnetic field, respectively. Since the value of H_E is much greater than that of H_C in the Co/Ni multilayer with 50 Å FeRh, we can confirm that strong exchange interaction exists at the AFM/FM interface. In order to further investigate the AFM thickness dependent features of the exchange bias system, we produced a number of samples having different thickness of the AFM FeRh layer from 10 Å to 50 Å and measured the respective magnetic hysteresis loop.

As shown in Fig. 2, different hysteresis loops were obtained as the thickness of the AFM FeRh layer varies. First, the magnetic hysteresis loops of the samples show almost perfect rectangular shape, which means the present systems maintain the perpendicular magnetic anisotropy well even if the AFM FeRh layer is adjacent to the FM Co/Ni multilayer regardless of t_{AFM}. Interestingly, as the t_{AFM} increases, the center position of the magnetic hysteresis loop placing at the origin gradually moves to the left for samples with t_{AFM}>25 Å. This means the exchange bias effect appears more and more from t_{AFM}=25 Å.

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For quantitative analysis, exact H_C and H_E were calculated using the relationships mentioned previously. As shown in Fig. 3, H_E is almost zero in the films of t_{AFM}<20 Å, however, it begins to arise from t_{AFM}=25 Å and gradually increases with thicker t_{AFM}. While it is predicted that the value of H_E is saturated after particular thickness t_{AFM}=∼50 Å, this is because only the AFM layer having an effective thickness affect on the exchange bias effect in the AFM/FM structure[1,2]. Non-linear change characteristics of the coercivity H_C is known to be due to the complex interaction between the FM and AFM magnetic domains appearing at interface. However, for Co/Pd and Co/Pt multilayers, the change characteristics of the H_C shows monotonically increasing tendency with respect to the thickness of AFM layer as same as the H_E[9], unlike the case of the present Co/Ni multilayer. In other words, the maximum AFM/FM magnetic domain wall interaction and the maximum H_E appear simultaneously in the same t_{AFM} for the Co/Pd and Co/Pt multilayers, whereas the maximum domain wall interaction occurs with thinner AFM layer than t_{AFM} where the H_E shows the maximum value in the present Co/Ni multilayer system. This implies that the H_C of the magnetization inversion in the Co/Ni multilayer is much more sensitive to the AFM/FM interface compared to the magnetization inversion of the Co/Pd and the Co/Pt multilayers.

In order to investigate the phenomenon of the magnetization inversion, we measured the inverted pattern of the magnetic domain in an exchange bias sample with t_{AFM}=50 Å showing an asymemetic hyteresis loop. The real-time magnetic domain revolution patterns were obtained in each region with the increasing and the decreasing magnetic field corresponding to the points of H_{C1} and H_{C2} in Fig. 1, respectively.

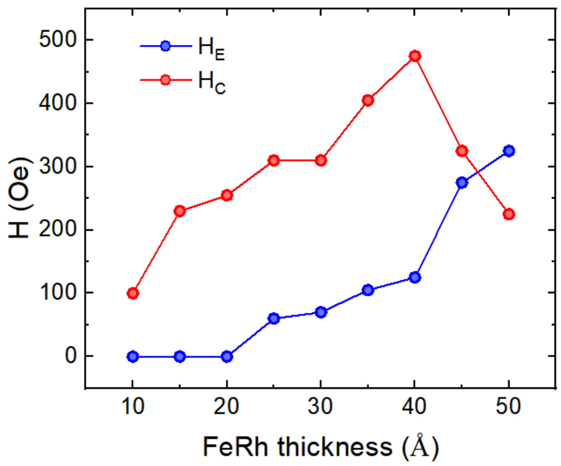

Figure 3. Dependence of the coercivity H_C and the exchange biased field H_E as a function of the AFM FeRh thickness, respectively. Here, the values of H_C and H_E were obtained using relations of $H_C=(H_{C1}H_{C2})/2$ and $H_E=(H_{C1}+H_{C2})/2$, respectively.

As shown in Fig. 4, inversion of magnetization in regions of the H_{C1} and the H_{C2} reveals a tendency of the domain wall movement, and there is not notable difference between the H_{C1} and the H_{C2} in perspective of the magnetic domain revolution pattern. Moreover, it was confirmed that only a single domain wall movement is visible in the both magnetic field area for all samples with various t_{AFM}. On the other hand, in the case of Co/Pt and Co/Pd multilayers[24,41,42], domain wall movement is completely different from the Co/Ni multilayer. Therefore, in the case of Co/Ni multilayer, it can be assumed that the complex interaction of the AFM/FM domain walls at the interface plays a key role rather than the asymmetric isotropic characteristics due to the exchange bias.

4. Conclusions

In this study, we produced exchange bias structure composed of the FM Co/Ni multilayer and the AFM FeRh layer having a perpendicular magnetic anisotropy. Changes of the exchange bias

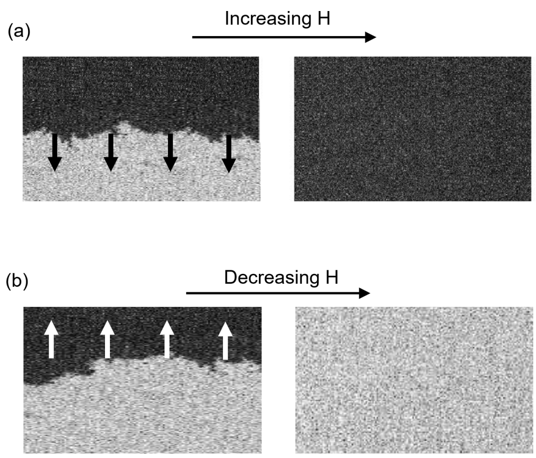

Figure 4. Domain revolution patterns with increasing H at (a)H_{C1} and with decreasing H at (b)H_{C2}. The black and white colors represent the different magnetization directions, respectively.

magnetic field H_E and the coercivity H_C was investigated by measuring the magnetic hysteresis loops. In particular, as a thickness of the AFM FeRh increases from 10 Å to 50 Å the exchange bias effect was started to appear from 25 Å, and such effect is continued to increase up to 50 Å. In perspective of the pattern of magnetic domain revolution, there is not a visible difference between the regions with increasing and decreasing magnetic field for the present Co/Ni multilayer adjacent to the AFM FeRh layer.

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1. Nogués, J.; Schuller, I.K. Exchange bias. *Journal of Magnetism and Magnetic Materials* **1999**, *192*, 203–232.
2. Koon, N. Calculations of exchange bias in thin films with ferromagnetic/antiferromagnetic interfaces. *Physical review letters* **1997**, *78*, 4865.
3. Ohldag, H.; Scholl, A.; Nolting, F.; Arenholz, E.; Maat, S.; Young, A.; Carey, M.; Stöhr, J. Correlation between exchange bias and pinned interfacial spins. *Physical review letters* **2003**, *91*, 017203.
4. Morales, R.; Li, Z.P.; Olamit, J.; Liu, K.; Alameda, J.; Schuller, I.K. Role of the antiferromagnetic bulk spin structure on exchange bias. *Physical review letters* **2009**, *102*, 097201.
5. Nogués, J.; Lederman, D.; Moran, T.; Schuller, I.K. Positive Exchange Bias in FeF_2-Fe Bilayers. *Physical review letters* **1996**, *76*, 4624.
6. Miltényi, P.; Gierlings, M.; Keller, J.; Beschoten, B.; Güntherodt, G.; Nowak, U.; Usadel, K.D. Diluted antiferromagnets in exchange bias: Proof of the domain state model. *Physical Review Letters* **2000**, *84*, 4224.
7. Mougin, A.; Mewes, T.; Jung, M.; Engel, D.; Ehresmann, A.; Schmoranzer, H.; Fassbender, J.; Hillebrands, B. Local manipulation and reversal of the exchange bias field by ion irradiation in FeNi/FeMn double layers. *Physical Review B* **2001**, *63*, 060409.
8. Roy, S.; Fitzsimmons, M.; Park, S.; Dorn, M.; Petracic, O.; Roshchin, I.V.; Li, Z.P.; Batlle, X.; Morales, R.; Misra, A.; others. Depth profile of uncompensated spins in an exchange bias system. *Physical review letters* **2005**, *95*, 047201.
9. Sort, J.; Baltz, V.; Garcia, F.; Rodmacq, B.; Dieny, B. Tailoring perpendicular exchange bias in [Pt/Co]-IrMn multilayers. *Physical Review B* **2005**, *71*, 054411.
10. Sort, J.; Dieny, B.; Fraune, M.; Koenig, C.; Lunnebach, F.; Beschoten, B.; Güntherodt, G. Perpendicular exchange bias in antiferromagnetic-ferromagnetic nanostructures. *Applied physics letters* **2004**, *84*, 3696–3698.

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11. Garcia, F.; Sort, J.; Rodmacq, B.; Auffret, S.; Dieny, B. Large anomalous enhancement of perpendicular exchange bias by introduction of a nonmagnetic spacer between the ferromagnetic and antiferromagnetic layers. *Applied physics letters* **2003**, *83*, 3537–3539.
12. Zhou, S.; Sun, L.; Searson, P.; Chien, C. Perpendicular exchange bias and magnetic anisotropy in CoO/permalloy multilayers. *Physical Review B* **2004**, *69*, 024408.
13. Radu, F.; Abrudan, R.; Radu, I.; Schmitz, D.; Zabel, H. Perpendicular exchange bias in ferrimagnetic spin valves. *Nature Communications* **2012**, *3*, 715.
14. Fitzsimmons, M.; Leighton, C.; Nogués, J.; Hoffmann, A.; Liu, K.; Majkrzak, C.; Dura, J.; Groves, J.; Springer, R.; Arendt, P.; others. Influence of in-plane crystalline quality of an antiferromagnet on perpendicular exchange coupling and exchange bias. *Physical review B* **2002**, *65*, 134436.
15. van Dijken, S.; Moritz, J.; Coey, J. Correlation between perpendicular exchange bias and magnetic anisotropy in IrMn/$[Co/Pt]_n$ and $[Pt/Co]_n$/IrMn multilayers. *Journal of applied physics* **2005**, *97*, 063907.
16. Echtenkamp, W.; Binek, C. Electric control of exchange bias training. *Physical review letters* **2013**, *111*, 187204.
17. He, X.; Wang, Y.; Wu, N.; Caruso, A.N.; Vescovo, E.; Belashchenko, K.D.; Dowben, P.A.; Binek, C. Robust isothermal electric control of exchange bias at room temperature. *Nature materials* **2010**, *9*, 579.
18. Egelhoff Jr, W.F.; McMichael, R.D.; Mallett, J.; Shapiro, A.J.; Powell, C.J.; Bonevich, J.E.; Judy, J.; Thomas, J.; Svedberg, E.B. Origin of exchange decoupling effects in high-coercivity air-annealed CoPd multilayers. *Journal of applied physics* **2005**, *97*, 10J104.
19. Suzuki, I.; Hamasaki, Y.; Itoh, M.; Taniyama, T. Controllable exchange bias in Fe/metamagnetic FeRh bilayers. *Applied Physics Letters* **2014**, *105*, 172401.
20. Nam, N.T.; Lu, W.; Suzuki, T. Exchange bias of ferromagnetic/antiferromagnetic in FePt/FeRh bilayers. *Journal of Applied Physics* **2009**, *105*, 07D708.
21. Jia, Z.; Misra, R. Simulated temperature dependence of exchange bias field in exchange coupled FeRh/FePt bilayer: relevance in magnetic recording media. *Materials Technology* **2010**, *25*, 307–312.
22. Marrows, C. Three-dimensional exchange bias in $\{Co/Pd\}_N$/FeMn. *Physical review B* **2003**, *68*, 012405.
23. Romanens, F.; Pizzini, S.; Yokaichiya, F.; Bonfim, M.; Pennec, Y.; Camarero, J.; Vogel, J.; Sort, J.; Garcia, F.; Rodmacq, B.; others. Magnetic relaxation of exchange biased Pt/Co multilayers studied by time-resolved Kerr microscopy. *Physical Review B* **2005**, *72*, 134410.
24. Czapkiewicz, M.; Stobiecki, T.; van Dijken, S. Thermally activated magnetization reversal in exchange-biased $[Pt/ Co]_3$/Pt/IrMn multilayers. *Physical Review B* **2008**, *77*, 024416.
25. Kagerer, B.; Binek, C.; Kleemann, W. Freezing field dependence of the exchange bias in uniaxial FeF_2–CoPt heterosystems with perpendicular anisotropy. *Journal of magnetism and magnetic materials* **2000**, *217*, 139–146.
26. Toyoki, K.; Shiratsuchi, Y.; Kobane, A.; Mitsumata, C.; Kotani, Y.; Nakamura, T.; Nakatani, R. Magnetoelectric switching of perpendicular exchange bias in Pt/Co/α-Cr2O3/Pt stacked films. *Applied Physics Letters* **2015**, *106*, 162404.
27. Ehresmann, A.; Lengemann, D.; Weis, T.; Albrecht, A.; Langfahl-Klabes, J.; Göllner, F.; Engel, D. Asymmetric Magnetization Reversal of Stripe-Patterned Exchange Bias Layer Systems for Controlled Magnetic Particle Transport. *Advanced Materials* **2011**, *23*, 5568–5573.
28. Stamps, R. Mechanisms for exchange bias. *Journal of Physics D: Applied Physics* **2000**, *33*, R247.
29. Kiwi, M. Exchange bias theory. *Journal of Magnetism and Magnetic materials* **2001**, *234*, 584–595.
30. Mangin, S.; Ravelosona, D.; Katine, J.; Carey, M.; Terris, B.; Fullerton, E.E. Current-induced magnetization reversal in nanopillars with perpendicular anisotropy. *Nature materials* **2006**, *5*, 210.
31. Tanigawa, H.; Koyama, T.; Yamada, G.; Chiba, D.; Kasai, S.; Fukami, S.; Suzuki, T.; Ohshima, N.; Ishiwata, N.; Nakatani, Y.; others. Domain wall motion induced by electric current in a perpendicularly magnetized Co/Ni nano-wire. *Applied Physics Express* **2009**, *2*, 053002.
32. Ryu, K.S.; Thomas, L.; Yang, S.H.; Parkin, S.S. Current induced tilting of domain walls in high velocity motion along perpendicularly magnetized micron-sized Co/Ni/Co racetracks. *Applied Physics Express* **2012**, *5*, 093006.
33. Koyama, T.; Hata, H.; Kim, K.J.; Moriyama, T.; Tanigawa, H.; Suzuki, T.; Nakatani, Y.; Chiba, D.; Ono, T. Current-induced magnetic domain wall motion in a Co/Ni nanowire with structural inversion asymmetry. *Applied Physics Express* **2013**, *6*, 033001.

34. Chiba, D.; Yamada, G.; Koyama, T.; Ueda, K.; Tanigawa, H.; Fukami, S.; Suzuki, T.; Ohshima, N.; Ishiwata, N.; Nakatani, Y.; others. Control of multiple magnetic domain walls by current in a Co/Ni nano-wire. *Applied Physics Express* **2010**, *3*, 073004.
35. Fukami, S.; Suzuki, T.; Tanigawa, H.; Ohshima, N.; Ishiwata, N. Stack structure dependence of Co/Ni multilayer for current-induced domain wall motion. *Applied physics express* **2010**, *3*, 113002.
36. Yoshimura, Y.; Koyama, T.; Chiba, D.; Nakatani, Y.; Fukami, S.; Yamanouchi, M.; Ohno, H.; Ono, T. Current-induced domain wall motion in perpendicularly magnetized Co/Ni nanowire under in-plane magnetic fields. *Applied Physics Express* **2012**, *5*, 063001.
37. Mohseni, S.M.; Yazdi, H.; Hamdi, M.; Brächer, T.; Mohseni, S.M. Current induced multi-mode propagating spin waves in a spin transfer torque nano-contact with strong perpendicular magnetic anisotropy. *Journal of Magnetism and Magnetic Materials* **2018**, *450*, 40–45.
38. Tang, M.; Zhao, B.; Zhu, W.; Zhu, Z.; Jin, Q.; Zhang, Z. Controllable Interfacial Coupling Effects on the Magnetic Dynamic Properties of Perpendicular [Co/Ni] 5/Cu/TbCo Composite Thin Films. *ACS applied materials & interfaces* **2018**, *10*, 5090–5098.
39. Kolesnikov, A.; Wu, H.; Stebliy, M.; Ognev, A.; Chebotkevich, L.; Samardak, A.; Han, X. Hybrid magnetic anisotropy [Co/Ni] 15/Cu/[Co/Pt] 4 spin-valves. *Journal of Magnetism and Magnetic Materials* **2018**, *449*, 271–277.
40. Jekal, S.; Rhim, S.; Hong, S.C.; Son, W.j.; Shick, A.B. Surface-termination-dependent magnetism and strong perpendicular magnetocrystalline anisotropy of an FeRh (001) thin film. *Physical Review B* **2015**, *92*, 064410.
41. Choe, S.B.; Shin, S.C. Magnetization reversal in nanostructured Co/Pd multilayers. *Physical Review B* **1998**, *57*, 1085.
42. Choe, S.B.; Shin, S.C. Observation of unequal activation volumes of wall-motion and nucleation processes in Co/Pd multilayers. *Physical review letters* **2001**, *86*, 532.