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Research Article

High Field Linear Magnetoresistance Sensors with Perpendicular Anisotropy $L1_0$-FePt Reference Layer

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High field linear magnetoresistance is an important feature for magnetic sensors applied in magnetic levitating train and high field positioning measurements. Here, we investigate linear magnetoresistance in Pt/FePt/ZnO/Fe/Pt multilayer magnetic sensor, where FePt and Fe ferromagnetic layers exhibit out-of-plane and in-plane magnetic anisotropy, respectively. Perpendicular anisotropy $L1_0$-FePt reference layer with large coercivity and high squareness ratio was obtained by in situ substrate heating. Linear magnetoresistance is observed in this sensor in a large range between +5 kOe and −5 kOe with the current parallel to the film plane. This $L1_0$-FePt based sensor is significant for the expansion of linear range and the simplification of preparation for future high field magnetic sensors.

1. Introduction

Research on spintronics is fast developing due to its widely practical application [1–4]. Magnetic tunnel junctions and magnetic spin valves as the important contents in spintronics are popularly used as magnetic sensors, such as magnetic read heads for hard-disk drive, position, and speed detectors in low magnetic field measurement [5, 6]. In general, the majority of the linear magnetic sensors are based on Hall effect or anisotropic magnetoresistance (AMR) with some shortcomings of poor thermal stability and limited operation frequency range [7]. Recently, the linear giant magnetoresistance (GMR) and tunneling magnetoresistance (TMR) sensors, in which a linear response can be achieved by applying a bias field [8], using a shape anisotropy of the free layer [9], or introducing a pinned layer [10], were proposed as promising candidates due to their high field sensitivity and good thermal stability [11–13]. Particularly, in some applications such as magnetic levitating train and high field positioning measurements, the high field linear magnetoresistance (MR) sensors are investigated due to high sensing field and fine repeatability [14, 15]. An approach of making a high field linear magnetic field response is to use a sandwich structure with a reference layer having high perpendicular magnetic anisotropy and an in-plane anisotropy free layer [16–19]. However some problems such as narrow linear range and complicated design are still unresolved.

In this work, we design and fabricate $L1_0$-FePt/ZnO/Fe multilayer films to shed light on this problem by choosing perpendicular anisotropy $L1_0$-FePt with a large coercive force (H_c) and a high squareness ratio as the reference layer. The MR curve is nearly linear when the applied field is in the range ±5 kOe measured at 300 K, which is improved greatly compared to previously reported results [18]. Meanwhile, this design simplifies effectively the structure of linear magnetic sensors through applying $L1_0$-FePt with a large H_c as reference layer.

2. Experimental

Multilayer films with a structure of Pt(4)/FePt(15)/ZnO(5)/Fe(5)/Pt(3) (thicknesses in nm) were prepared on single crystal MgO (001) substrates by magnetron sputtering system as shown schematically in Figure 1(a). A high field linear MR sensor is designed using a perpendicular anisotropy $L1_0$-FePt reference layer and in-plane anisotropy Fe free layer separated by a ZnO barrier layer in the magnetic multilayers as shown in Figure 1(b). Here the free and reference layers

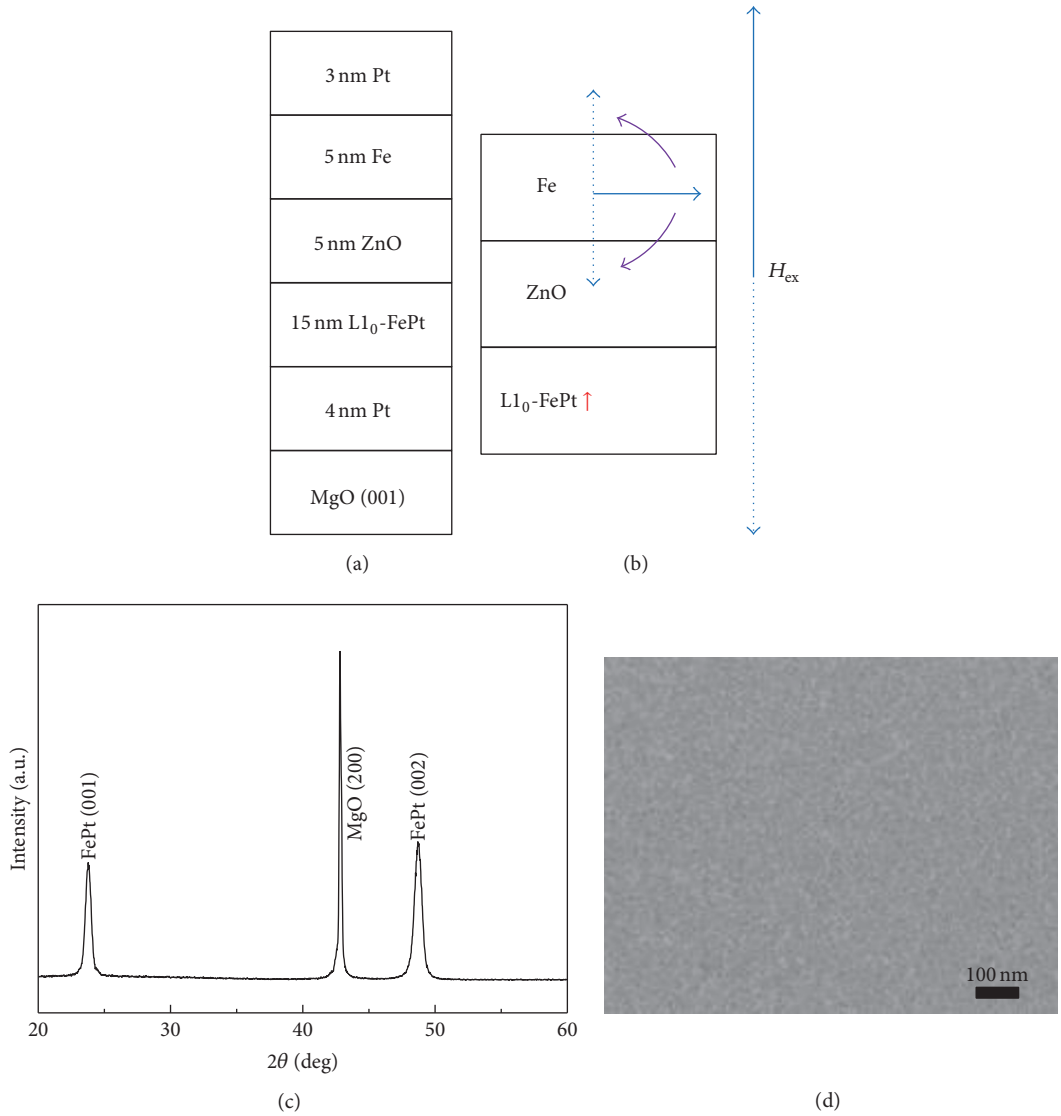

Figure 1: (a) Schematics of the Pt(4)/FePt(15)/ZnO(5)/Fe(5)/Pt(3) multilayers on MgO substrate; (b) the core sandwich schematic diagram of L1$_0$-FePt/ZnO/Fe. The magnetization directions are marked by arrows, and the applied external magnetic field is perpendicular to the film plane; (c) XRD spectra of the Pt(4)/L1$_0$-FePt(15) bilayer films; (d) SEM image of the Pt(4)/L1$_0$-FePt(15) bilayer film surface.

are perpendicular to each other. With the increase of external magnetic field (H_{ex}), the free layer's magnetization rotates until becoming perpendicular to the film plane. And a reversible linear MR response in a large range of magnetic field was expected.

The pressure of high-purity argon was 2.0 Pa during sputtering. The Pt and FePt layers were deposited at an in situ temperature of 450°C followed by annealing for 2 h at 450°C. Then the ZnO, Fe, and Pt layers were successively deposited at the room temperature after the deposition of FePt layer. The FePt film was manufactured by cosputtering an Fe target and a Pt target, whose deposition rates were calibrated to achieve $Fe_{55}Pt_{45}$. The base vacuum was under 8.0×10^{-5} Pa. The crystalline structures and microstructure of multilayer films were characterized by means of X-ray diffraction (XRD) and transmission electron microscope (TEM). The morphologies of the samples were observed by scanning electron microscopy (SEM). The magnetic properties of films were determined using a superconduction quantum inference device (SQUID) and a vibrating sample magnetometer (VSM). The magnetic field dependence of MR was measured using a four-point method with current-in-plane (CIP) and applied field perpendicular to plane using a Keithley 2400 source meter and Keithley 2182 nanovolt meter in a physical property measurement system (PPMS, Quantum Design Inc.).

3. Results and Discussion

XRD pattern of the thin film with Pt/L1$_0$-FePt bilayers is shown in Figure 1(c). The peaks of (001) and (002) were

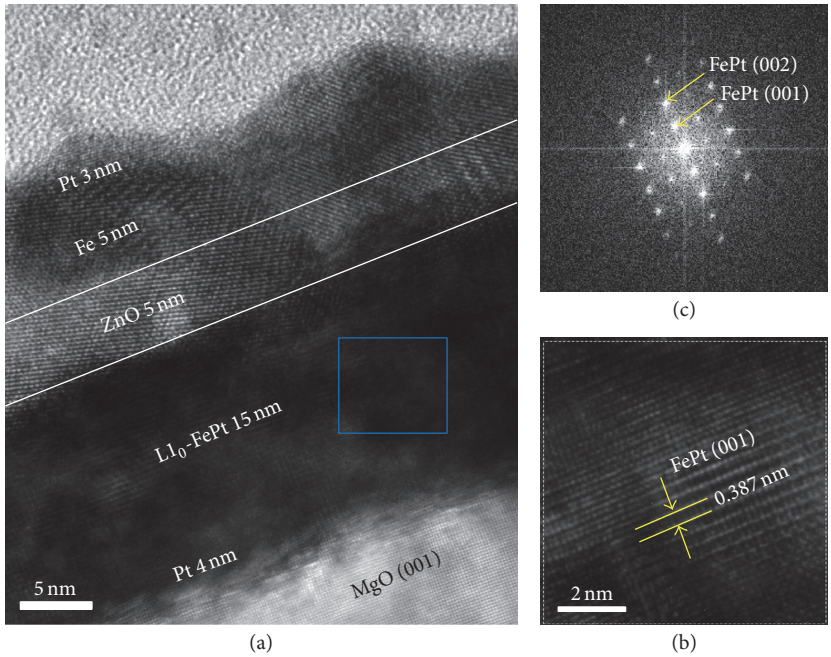

Figure 2: TEM analysis of the Pt(4)/FePt(15)/ZnO(5)/Fe(5)/Pt(3) multilayers. (a) The cross section TEM image. (b) The HRTEM image. (c) Its corresponding FFT image.

observed for FePt film, indicating formation of the $L1_0$ ordered phase with easy axis perpendicular to the substrate surface. Thus, the transformation of FePt film from face-centered cubic (fcc) phase to face-centered tetragonal (fct) phase was fulfilled by in situ substrate heating. The SEM image shows that the deposited Pt/$L1_0$-FePt bilayer surface is continuous and smooth (see Figure 1(d)). The lattice misfit between FePt (001) and MgO (001) is 8.8% [20]; the FePt film received tensile stress along the in-plane direction, which causes the film tend to form granular film [21]. Whereas the mismatch value is 1.8% between Pt (001) and MgO (001) [22], the Pt buffer layer deposited between MgO substrate and FePt film effectively reduces the stress, causing the forming of a continuous film.

In order to reflect the structure information of the multilayers more accurately, we carried out the cross section TEM image and high-resolution TEM (HRTEM) image of the Pt(4)/FePt(15)/ZnO(5)/Fe(5)/Pt(3) multilayer sensor. The result present that the films are continuous as shown in Figure 2(a). The structure of the multilayer films is consistent with the schematic structure in Figure 1(a). From the HRTEM image shown in Figure 2(b), the lattice fringe spacing is measured to be 0.387 nm, corresponding to the $d_{\mathrm{FePt}\,(001)}$ (0.384 nm) of $L1_0$-FePt phase [23]. Also, the FePt (001) and FePt (002) can be found obviously from its fast Fourier transform (FFT) image in Figure 2(c), suggesting that $L1_0$ ordered phase of FePt was obtained in our films.

Figure 3(a) shows the magnetic hysteresis loops of Pt(4)/FePt(15) films deposited in situ substrate heating at 450°C. The coercivity (H_c) of out-of-plane and in-plane films is 7 kOe and 4 kOe, respectively. The remanence (M_r) of out-of-plane and in-plane direction is 610 emu/cm^3 and 176 emu/cm^3, respectively. The squareness ratios (M_r/M_s) of in-plane and out-of-plane are about 0.5 and 0.9, respectively. These data indicate the preferred alignment of the easy magnetization axis along the out-of-plane direction, which agrees with the result of Figure 1(c). It should be mentioned that the saturation magnetization (M_s) of out-of-plane is larger than that of in-plane as shown in Figure 3(a). This may be due to the fact that M_s of in-plane is not completely saturated under the maximum applied field of 3 Tesla, which has been reported in other publications about $L1_0$-FePt films [24, 25]. The ZnO barrier layer, Fe free layer, and Pt protective layer were deposited on the Pt/FePt film at room temperature to prepare the $L1_0$-FePt based sensor. The in-plane and out-of-plane magnetic hysteresis loops of Pt(4)/FePt(15)/ZnO(5)/Fe(5)/Pt(3) multilayers are shown in Figure 3(b). There hardly exists coupling between top Fe free layer and bottom FePt reference layer for arising apparent kinks in it. The magnetization of multilayers reversal process (represented by arrows) can be understood precisely in out-of-plane loop when external magnetic field is applied perpendicular to film plane. The free layer is aligned perpendicular to reference layer when external magnetic field hits zero (point O). When magnetic field reached −7 kOe (or +7 kOe) (point A or B), the bottom FePt would begin to reverse from the up (down) to down (up) perpendicular to the films.

A typical MR curve of a nonpatterned sample is shown in Figure 4, showing regular current-in-plane (CIP) MR effect with an applied magnetic field out of the film plane. The

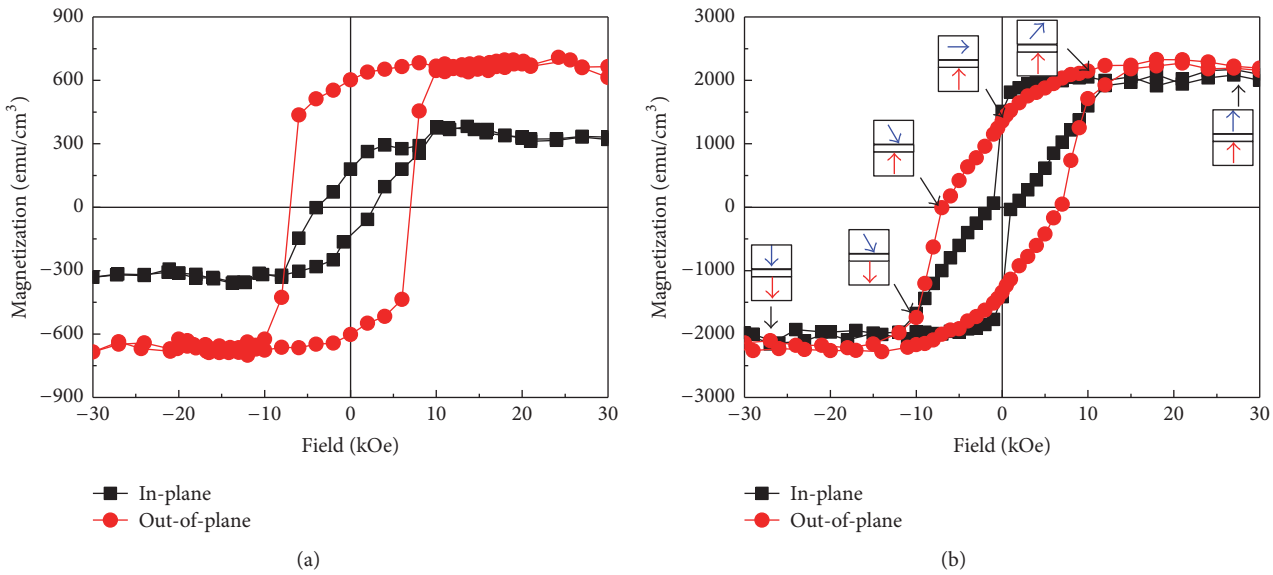

Figure 3: In-plane and out-of-plane magnetic hysteresis loops. (a) The Pt(4)/$L1_0$-FePt(15) bilayers. (b) The Pt(4)/$L1_0$-FePt(15)/ZnO(5)/Fe(5)/Pt(3) multilayers. The arrows show the magnetization reversal process of the Fe free layer (top blue) and FePt reference layer (bottom red) in the out-of-plane loop in (b).

MR values are found to be 0.5% and 1.2% measured at room temperature and 10 K, respectively. A double-peak feature at the coercive fields can be observed in the curves, which is in agreement with the magnetic hysteresis loop in Figure 3. Here, the MR is defined as MR = $[R(H) - R(\max)]/R(\max) \times 100\%$, where $R(H)$ and $R(\max)$ are the resistance at external field H and the maximum resistance, respectively. This value is the typical magnitude of MR in $L1_0$-FePt based multilayers [14, 26, 27], because that ZnO cannot be perfectly grown on $L1_0$-FePt layer as shown Figure 3(a). Besides, we believe that the MR value of the film may be higher due to the fact that the MR curve is not saturated at 20 kOe, and the MR ratio might obtain a higher value if a higher magnetic field was applied to our sample.

The expected high field linear characteristic and non-hysteretic variation of the MR with highly reversibility is obtained when the magnetic field varies between +5 kOe and −5 kOe at room temperature as shown in Figure 4(c). The sensitivity is 0.2%/T in the MTJ composed of Pt(4)/FePt(15)/ZnO(5)/Fe(5)/Pt(3) multilayers. The magnetic configuration and the resistance evolve with the field as shown in Figure 4(c). When the applied field is +5 kOe, the magnetization direction of the $L1_0$-FePt layer points out-of-plane and the one of the Fe layer is not completely parallel to the magnetization of $L1_0$-FePt layer (see point A in Figure 4(c)) due to the fact that the magnetic loop and MR are not saturated at 5 kOe shown in Figures 3(b) and 4(a). At this point (point M), the device has a smaller resistance. The value of resistance increases linearly with decreasing magnetic field until the field is reduced to zero at point O, where the magnetization of the Fe layer is rotated to perpendicular to the one of $L1_0$-FePt layer. With the magnetic field increases in the reverse direction, the resistance continues to increase until the magnetic field reaches −5 kOe at point N. It is important to note that the magnetization of $L1_0$-FePt layer is always invariant throughout the process, which plays a key role in the MR linear variation with the magnetic field.

4. Conclusion

In summary, linear MR in Pt/FePt/ZnO/Fe/Pt multilayer magnetic sensor was investigated. In this design, perpendicular anisotropy $L1_0$-FePt reference layer and in-plane anisotropy Fe free layer separated by ZnO barrier layer are perpendicular to each other. The $L1_0$-FePt film with large coercivity and high squareness ratio was obtained by in situ substrate heating. The MR values of 0.5% and 1.2% were obtained at room temperature and 10 K, respectively. Linear MR response is observed in this sensor in a large range between +5 kOe and −5 kOe at room temperature. This $L1_0$-FePt based linear MR is significant for high field linear magnetic sensors.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

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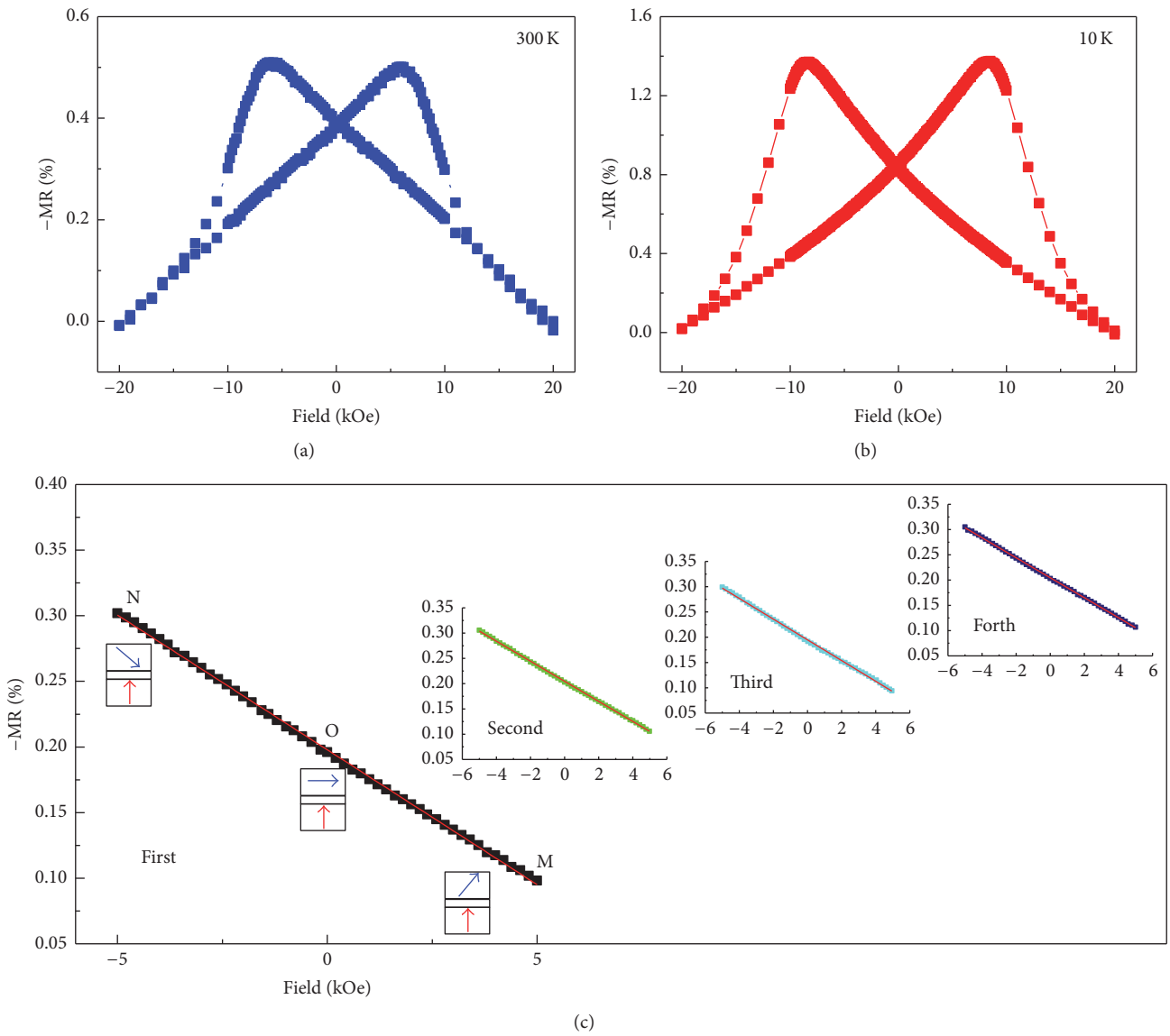

Figure 4: The MR of the multilayer films measured at 300 K (a) and 10 K (b); (c) the linear magnetic field response of the multilayer films when the external field varies between +5 kOe and −5 kOe at 300 K. The insets in (c) show the three repeated measures of MR curve of the same sample.

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References

[1] I. Žutić, J. Fabian, and S. D. Sarma, "Spintronics: fundamentals and applications," *Reviews of Modern Physics*, vol. 76, no. 2, pp. 323–410, 2004.

[2] K. Inomata, N. Ikeda, N. Tezuka et al., "Highly spin-polarized materials and devices for spintronics," *Science and Technology of Advanced Materials*, vol. 9, no. 1, Article ID 014101, 19 pages, 2008.

[3] F. Pan, C. Song, X. J. Liu, Y. C. Yang, and F. Zeng, "Ferromagnetism and possible application in spintronics of transition-metal-doped ZnO films," *Materials Science and Engineering R: Reports*, vol. 62, no. 1, pp. 1–35, 2008.

[4] D. Boldrin and A. S. Wills, "Anomalous Hall effect in geometrically frustrated magnets," *Advances in Condensed Matter Physics*, vol. 2012, Article ID 615295, 12 pages, 2012.

[5] H. X. Wei, Q. H. Qin, M. Ma, R. Sharif, and X. F. Han, "80% tunneling magnetoresistance at room temperature for thin Al-O barrier magnetic tunnel junction with CoFeB as free and reference layers," *Journal of Applied Physics*, vol. 101, no. 9, Article ID 09B501, 3 pages, 2007.

[6] S. S. P. Parkin, C. Kaiser, A. Panchula et al., "Giant tunnelling magnetoresistance at room temperature with MgO (100) tunnel barriers," *Nature Materials*, vol. 3, no. 12, pp. 862–867, 2004.

[7] T. R. Mcguire and R. I. Potter, "Anisotropic magnetoresistance in ferromagnetic 3D alloys," *IEEE Transactions on Magnetics*, vol. 11, no. 4, pp. 1018–1038, 1975.

[8] X. Liu, C. Ren, and G. Xiao, "Magnetic tunnel junction field sensors with hard-axis bias field," *Journal of Applied Physics*, vol. 92, no. 8, pp. 4722–4725, 2002.

[9] P. Wiśniowski, J. M. Almeida, S. Cardoso, N. P. Barradas, and P. P. Freitas, "Effect of free layer thickness and shape anisotropy on the transfer curves of MgO magnetic tunnel junctions," *Journal of Applied Physics*, vol. 103, no. 7, Article ID 07A910, 3 pages, 2008.

[10] J. Y. Chen, J. F. Feng, and J. M. D. Coey, "Tunable linear magnetoresistance in MgO magnetic tunnel junction sensors using two pinned CoFeB electrodes," *Applied Physics Letters*, vol. 100, no. 14, Article ID 142407, 4 pages, 2012.

[11] H. X. Wei, Q. H. Qin, Z. C. Wen, X. F. Han, and X.-G. Zhang, "Magnetic tunnel junction sensor with Co/Pt perpendicular anisotropy ferromagnetic layer," *Applied Physics Letters*, vol. 94, no. 17, Article ID 172902, 2009.

[12] S. Ikeda, J. Hayakawa, Y. Ashizawa et al., "Tunnel magnetoresistance of 604% at 300 *K* by suppression of Ta diffusion in CoFe*B*/Mg*O*/CoFe*B* pseudo-spin-valves annealed at high temperature," *Applied Physics Letters*, vol. 93, no. 8, Article ID 082508, 2008.

[13] S. Yuasa, T. Nagahama, A. Fukushima, Y. Suzuki, and K. Ando, "Giant room-temperature magnetoresistance in single-crystal Fe/MgO/Fe magnetic tunnel junctions," *Nature Materials*, vol. 3, no. 12, pp. 868–871, 2004.

[14] Q. H. Qin, H. X. Wei, and X. F. Han, "Linear magnetic field response spin valve with perpendicular anisotropy ferromagnet layer," *Journal of Applied Physics*, vol. 103, no. 7, Article ID 07E906, 3 pages, 2008.

[15] C. Song, Y. Y. Wang, X. J. Li, G. Y. Wang, and F. Pan, "Interlayer magnetostatic coupling and linear magnetoresistance in [Pd/Co]/MgO/Co junction sensor," *Applied Physics Letters*, vol. 101, no. 6, Article ID 062404, 4 pages, 2012.

[16] H. Naganuma, G. Kim, Y. Kawada et al., "Electrical detection of millimeter-waves by magnetic tunnel junctions using perpendicular magnetized $L1_0$-FePd free layer," *Nano Letters*, vol. 15, no. 1, pp. 623–628, 2015.

[17] M. Yoshikawa, E. Kitagawa, T. Nagase et al., "Tunnel magnetoresistance over 100% in MgO-based magnetic tunnel junction films with perpendicular magnetic L10-FePt electrodes," *IEEE Transactions on Magnetics*, vol. 44, no. 11, pp. 2573–2576, 2008.

[18] T. Shima, K. Takanashi, Y. K. Takahashi, and K. Hono, "Coercivity exceeding 100 kOe in epltaxially grown FePt sputtered films," *Applied Physics Letters*, vol. 85, no. 13, pp. 2571–2573, 2004.

[19] P. Ho, G. Han, K. He, G. M. Chow, and J. S. Chen, "Ultra-thin $L1_0$-FePt for perpendicular anisotropy $L1_0$-FePt/Ag/$[Co/Pd]_{30}$ pseudo spin valves," *Journal of Applied Physics*, vol. 115, no. 17, Article ID 17C102, 3 pages, 2014.

[20] B. Laenens, F. M. Almeida, N. Planckaert et al., "Interplay between structural and magnetic properties of $L1_0$ -FePt (001) thin films directly grown on MgO(001)," *Journal of Applied Physics*, vol. 105, no. 7, Article ID 073913, 6 pages, 2009.

[21] K. F. Dong, H. H. Li, and J. S. Chen, "Lattice mismatch-induced evolution of microstructural properties in FePt films," *Journal of Applied Physics*, vol. 113, no. 23, Article ID 233904, 10 pages, 2013.

[22] R. F. C. Farrow, D. Weller, R. F. Marks, M. F. Toney, A. Cebollada, and G. R. Harp, "Control of the axis of chemical ordering and magnetic anisotropy in epitaxial FePt films," *Journal of Applied Physics*, vol. 79, no. 8, pp. 5967–5969, 1996.

[23] J. Kim, C. Rong, Y. Lee, J. P. Liu, and S. Sun, "From core/shell structured FePt/Fe_3O_4/MgO to ferromagnetic FePt nanoparticles," *Chemistry of Materials*, vol. 20, no. 23, pp. 7242–7245, 2008.

[24] C. Feng, Q. Zhan, B. Li et al., "Magnetic properties and microstructure of FePt/Au multilayers with high perpendicular magnetocrystalline anisotropy," *Applied Physics Letters*, vol. 93, no. 15, Article ID 152513, 2008.

[25] C. Feng, E. Zhang, C. C. Xu et al., "Magnetic properties and microstructure of $L1_0$-FePt/AlN perpendicular nanocomposite films," *Journal of Applied Physics*, vol. 110, no. 6, Article ID 063910, 5 pages, 2011.

[26] P. Ho, G. C. Han, R. F. L. Evans, R. W. Chantrell, G. M. Chow, and J. S. Chen, "Perpendicular anisotropy L 10 -FePt based pseudo spin valve with Ag spacer layer," *Applied Physics Letters*, vol. 98, no. 13, Article ID 132501, 3 pages, 2011.

[27] S. Van Dijken and J. M. D. Coey, "Magnetoresistance sensor with an out-of-plane magnetized sensing layer," *Applied Physics Letters*, vol. 87, no. 2, Article ID 022504, 3 pages, 2005.