AIP | Applied Physics Letters

Tuning anomalous Hall conductivity in L 1 0 FePt films by long range chemical ordering

M. Chen, Z. Shi, W. J. Xu, X. X. Zhang, J. Du, and S. M. Zhou

Citation: Applied Physics Letters **98**, 082503 (2011); doi: 10.1063/1.3556616
View online: http://dx.doi.org/10.1063/1.3556616
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/98/8?ver=pdfcov
Published by the AIP Publishing

Tuning anomalous Hall conductivity in $L1_0$ FePt films by long range chemical ordering

M. Chen,[1] Z. Shi,[1,2,a)] W. J. Xu,[3] X. X. Zhang,[4] J. Du,[5] and S. M. Zhou[1,2]
[1]*Department of Physics and Surface Physics State Laboratory, Fudan University, Shanghai 200433, People's Republic of China*
[2]*Department of Physics, Tongji University, Shanghai 200092, People's Republic of China*
[3]*Department of Physics and Institute of Nanoscience and Technology, The Hong Kong University of Science and Technology (HKUST), Clear Water Bay, Kowloon, Hong Kong*
[4]*Image-Characterization Core Laboratory, Research and Development, King Abdullah University of Science and Technology, Thuwal 23955-6900, Saudi Arabia*
[5]*National Laboratory of Solid State Microstructures, Nanjing University, Nanjing 210093, People's Republic of China*

(Received 14 December 2010; accepted 29 January 2011; published online 24 February 2011)

For $L1_0$ FePt films, the anomalous Hall conductivity $\sigma_{xy}=-a\sigma_{xx}-b$, where $a=a_0f(T)$, $b=b_0f(T)$, and $f(T)$ is the temperature dependence factor of the spontaneous magnetization. With increasing chemical long range ordering S, a_0 changes its sign accompanied by a reduction of its magnitude and b_0 increases monotonically. The spin-orbit coupling strength is suggested to increase with increasing S. As an approach, the long range chemical ordering can be used to control the anomalous Hall effect in ferromagnetic alloy films. © *2011 American Institute of Physics*.
[doi:10.1063/1.3556616]

Anomalous Hall effect (AHE) in ferromagnetic metallic films, particularly in 3*d* transition metallic films, has been studied extensively because of its intriguing physics.[1–12] Two major issues are concerned, i.e., the scaling law between the AHE resistivity ρ_{xy} and the longitudinal one ρ_{xx} and the effect of spin-orbit coupling (SOC) on the anomalous Hall conductivity (AHC). The scaling law of $\rho_{xy}=a\rho_{xx}+b\rho_{xx}^2$ is shown both theoretically and experimentally, where the first term arises from the extrinsic skew scattering at impurity sites and the second one corresponds to the extrinsic side-jump and the intrinsic Karplus–Luttinger terms.[2–4,6,7] Accordingly, the AHC $\sigma_{xy}\simeq-a\sigma_{xx}-b$ when $\rho_{xy}\ll\rho_{xx}$, where $\sigma_{xx}=1/\rho_{xx}$. When a and b are *a priori* assumed to be temperature (T)-independent, σ_{xy} has a linear dependence on σ_{xx}. As for the second issue, the SOC effect on the AHC has been studied theoretically.[7,8,10] It is a great experimental challenge because it is hard to find ferromagnetic materials in which the SOC strength $\Delta_{SOC}(=\xi\vec{l}\cdot\vec{s})$ can be easily tuned while the exchange split energy is fixed. Very recently, the effect of the SOC on the AHC has been studied by using $L1_0$ FePt and FePd films,[12] in which a and b were still believed to be T-independent despite the low Curie temperatures of these films. In this letter, we have studied the effect of the chemical ordering on the AHC in $L1_0$ FePt films. a and b below 300 K are of the same temperature dependence factor as the spontaneous magnetization M_S. At the specific temperature, the values of a and b depends on the chemical ordering degree S. This work will facilitate the design and fabrication of AHE devices and also shed light on the understanding of large perpendicular magnetic anisotropy in $L1_0$ FePt films.

A series of 10 nm $L1_0$ $Fe_{50}Pt_{50}$ (=FePt) films with varying S were grown on MgO(001) substrates by dc magnetron sputtering at different substrate temperatures. The microstructure and the film thickness were identified by x-ray diffraction (XRD) and x-ray reflectivity (XRR), respectively. The films were patterned into normal Hall bar and the Hall resistance ρ_H was measured from 5 to 300 K. The longitudinal resistance ρ_{xx} was also measured in the same T regime at zero external magnetic field. In experiments, the magnetoresistance of all samples is less than 0.5%. M_S was measured as a function of T by the physical property measurement system of Quantum Design Inc.

Deposited at ambient temperature, the FePt film is of the fcc structure with (111) preferred orientation. At high substrate temperatures, $L1_0$ (001) and (002) peaks appear near $2\theta=24°$ and $2\theta=48°$, respectively, as shown in Fig. 1(a). S was calculated from the intensities of (001) and (002) peaks[13] and is found to increase from 0 to 0.74 when the substrate temperature is raised. Since the lattice constant along the c axis decreases from 0.382 to 0.374 nm, the long range chemical ordering and the lattice distortion happen simultaneously. Due to its crucial importance in measurements of ρ_{xy} and ρ_{xx}, the film thickness was measured by XRR at small angles, as shown in Fig. 1(b), and found to be 10 ± 0.5 nm.

Figure 1(c) shows typical Hall loops at 5 K. For $S=0$, the Hall loop is slanted with the hard axis along the film normal direction. For large S, the loop becomes squared with large coercivity, exhibiting perpendicular magnetic anisotropy. In the Hall loop of ferromagnetic films, Hall resistivity $\rho_H=R_OH+4\pi M(H)R_S$, where R_O and R_S are coefficients of ordinary and anomalous Hall effects, respectively. By extrapolating the saturation curve of ρ_H versus H, ρ_{xy} is achieved and found to decrease for large S.[14] As shown in Fig. 1(d), for $S=0.74$, the normalized M_S decreases by about 15% with T rising from 5 to 300 K. Apparently, the M_S reduction cannot be ignored because the Curie temperature of 700–750 K is not sufficiently high.[15] Moreover, for $S=0.74$, M_S obeys T^2 linear dependence, hinting either the excitation of interacting spin waves or long-wavelength,

a)Author to whom correspondence should be addressed. Electronic mail: shizhong@tongji.edu.cn.

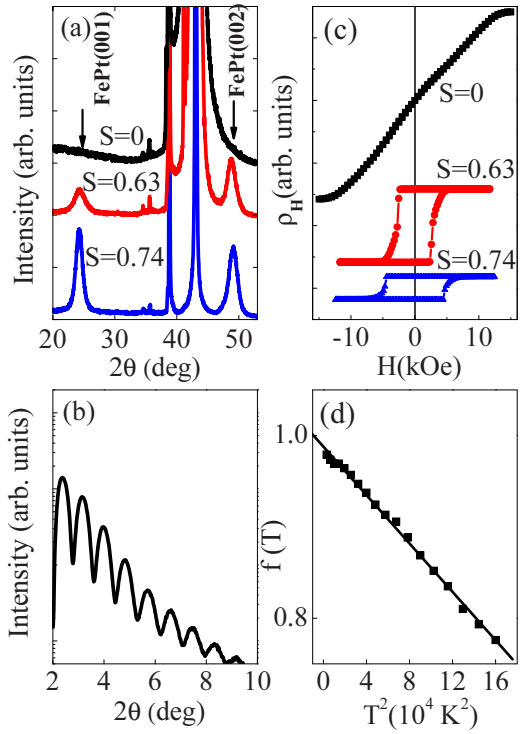

FIG. 1. (Color online) (a) Typical XRD spectra at high angles and (b) XRR at low angles, (c) Hall loops at 5 K, and (d) the T dependence factor $f(T)$. In (b) and (d), S=0.74. In (d), the line refers to linear fit results.

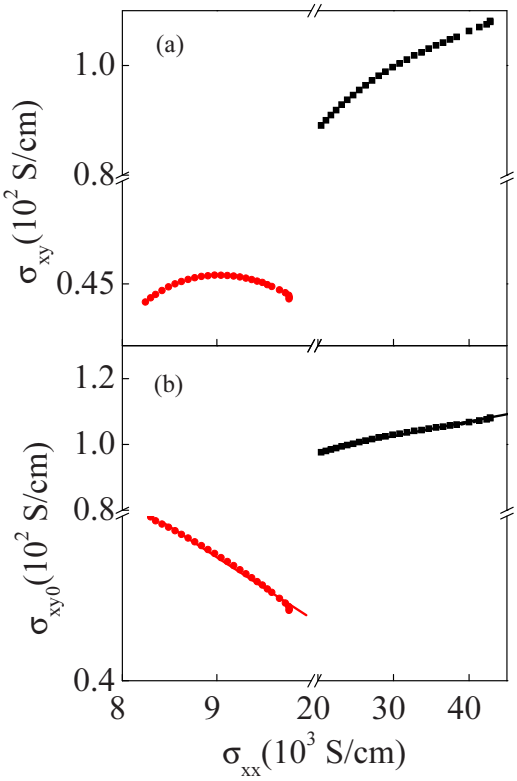

FIG. 3. (Color online) (a) σ_{xy} and (b) σ_{xy0} vs σ_{xx} for S=0.74 (squares) and 0 (circles). The lines in (b) refer to linear fit results.

low-frequency fluctuations.[9,16] For all samples, one has $M_S = M_0 f(T)$, where M_0 and $f(T)$ are the spontaneous magnetization at 0 K and the T dependence factor, respectively.

Figures 2(a) and 2(b) show that ρ_{xx} and ρ_{xy} both increase with T but decrease with S. ρ_{xx} approaches the residual resistance ρ_0 near T=0 K. At high T, the T dependence of ρ_{xx} can be approximately fitted by a linear function of T^2, indicating the contribution of spin flip scattering as observed in other itinerant ferromagnets.[17,18] This is because the one-magnon scattering process leads to the T^2 dependence of the resistivity when there are spin-up and spin-down electrons at the Fermi surface. ρ_0 becomes small for high S, possibly due to both the improvement of the crystalline quality and reduction of the density of static defects at elevated substrate temperatures.

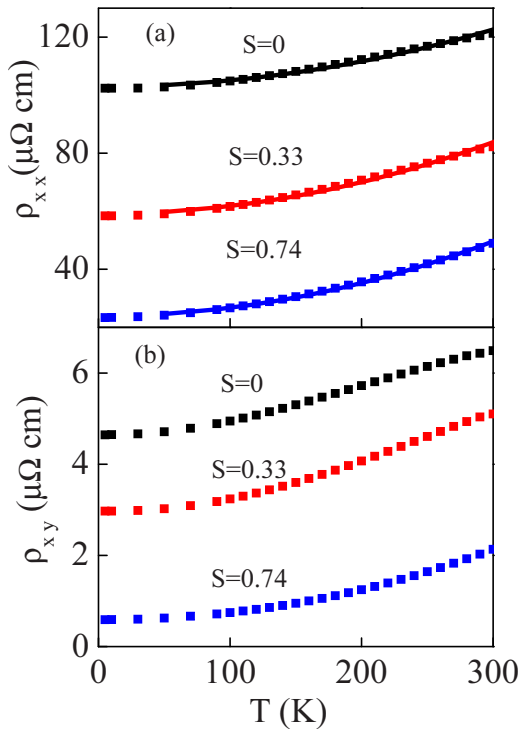

FIG. 2. (Color online) (a) ρ_{xx} and (b) ρ_{xy} vs T for FePt films with various S. The solid lines in (a) refer to the T^2 fit results.

Figure 3(a) shows typical curves of σ_{xy} versus σ_{xx} as a function of T. Apparently, for all samples, results cannot be described either by the relationship of $\sigma_{xy} \propto \sigma_{xx}^n$ or by the linear function of σ_{xx}.[19] As analyzed below, this is because for $L1_0$ FePt films, the effect of varying M_S cannot be neglected due to the low Curie temperature and thus a and b are T-dependent. Actually, the intrinsic AHC is proved to be proportional to M_S as a function of T by both the Karplus–Luttinger model and the integration of the Berry curvature.[2,9] The same dependence has been observed in Ni alloys, Heusler alloys (CoMnSb, NiMnSb, and Co_2CrAl), Si-based magnetic semiconductors, and other ferromagnetic compounds.[9,17,20–24] It has also been pointed out that the skew scattering contribution to the AHC is also proportional to M_S.[10,25] Therefore, one has the following relationship:

$$a = a_0 f(T), \tag{1}$$

$$b = b_0 f(T), \tag{2}$$

$$\sigma_{xy} = \sigma_{xy0} f(T), \tag{3}$$

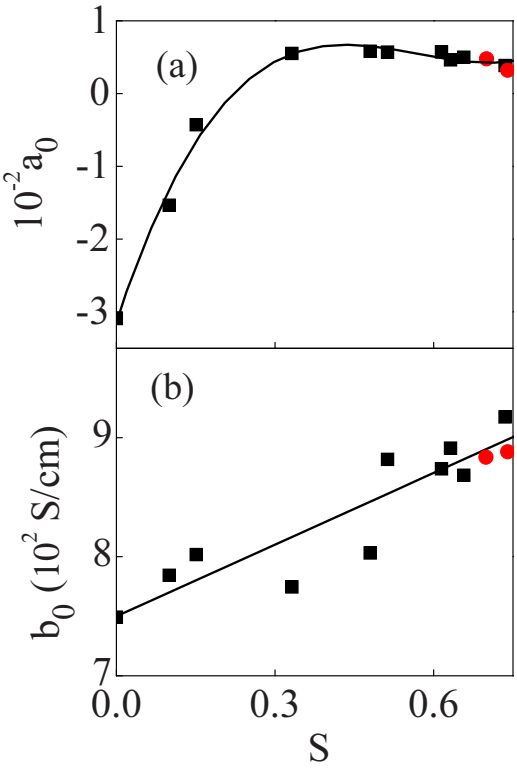

FIG. 4. (Color online) (a) a_0 and (b) b_0 as a function of S for 10 nm $L1_0$ FePt films (solid squares). In comparison, the data points of 20 nm $L1_0$ FePt films (solid circles) are given. Solid lines serve a guide to the eye.

$$\sigma_{xy0} = -a_0\sigma_{xx} - b_0. \quad (4)$$

Fortunately, the measured σ_{xy0} can be fitted by a linear function of σ_{xx}, as shown in Fig. 3(b). Such salient linear dependence, in turn, proves the validity of the assumption that for FePt films, a and b are proportional to M_S in the sampling T region. They are equal to a_0 and b_0 at $T=0$ K and approach zero near Curie temperature. In contrast, for magnetic materials with high Curie temperatures such as Fe and Co, M_S in the T region from 5 to 300 K is almost constant, leading to T-independent a and b.

Figures 4(a) and 4(b) show the variations of a_0 and b_0 with S. a_0 changes from the large negative to the small positive when S increases from zero to 0.74. This is caused simultaneously by the extrinsic attribute of a_0 and the reduction of the static defects at high S.[26] b_0 is equal to 750 S/cm for $S=0$ and increases up to 920 S/cm at high S. For comparison, the data of a_0 and b_0 are given for 20 nm $L1_0$ FePt films. Since the value of b_0 is almost identical for different thickness, it is suggested to come from the intrinsic Karplus–Luttinger term. Furthermore, the intrinsic AHC is theoretically predicted to increase linearly at small SOC and to reach saturation for large SOC.[7] Since the exchange split energy changes little, as demonstrated by the experimental evidence that the effective spin magnetic moment does not change much during the phase transformation from the disordered to the ordered,[27,28] the variation of b_0, in turn, indicates the enhancement of the SOC strength, which is also demonstrated by the enhancement of magneto-optical Kerr effect and spin Hall effect.[29,30] For the disordered FePt films, opposite signs of a_0 and b_0 indicate that the skew scattering contributes to the AHC in an opposite way to that of the Karplus–Luttinger term, as observed in bcc Fe films.[11]

In a short summary, for $L1_0$ FePt films, the T^2 dependence of ρ_{xx} has been observed. For a specific S, $\sigma_{xy} = \sigma_{xy0}f(T)$ and $\sigma_{xy0} = -a_0\sigma_{xx} - b_0$. For a_0, the sign changes and its magnitude is reduced with increasing S. More remarkably, b_0 increases slightly and the Δ_{SOC} is enhanced by the chemical ordering. The present state of the art results will also be helpful to study electronic structure of $L1_0$ FePt films.

This work was supported by NSFC Grant Nos. 50871030 and 10974032 and the National Basic Research Program of China under Grant No. 2009CB929201.

[1]E. H. Hall, Philos. Mag. **12**, 157 (1881).
[2]R. Karplus and J. M. Luttinger, Phys. Rev. **95**, 1154 (1954).
[3]J. Smit, Physica (Amsterdam) **24**, 39 (1958).
[4]L. Berger, Phys. Rev. B **2**, 4559 (1970).
[5]A. Fert and O. Jaoul, Phys. Rev. Lett. **28**, 303 (1972).
[6]T. Jungwirth, Q. Niu, and A. H. MacDonald, Phys. Rev. Lett. **88**, 207208 (2002).
[7]Y. G. Yao, L. Kleinman, A. H. MacDonald, J. Sinova, T. Jungwirth, D. S. Wang, E. Wang, and Q. Niu, Phys. Rev. Lett. **92**, 037204 (2004).
[8]P. Wölfle and K. A. Muttalib, Ann. Phys. **15**, 508 (2006).
[9]C. G. Zeng, Y. G. Yao, Q. Niu, and H. H. Weitering, Phys. Rev. Lett. **96**, 037204 (2006).
[10]N. A. Sinitsyn, A. H. MacDonald, T. Jungwirth, V. K. Dugaev, and J. Sinova, Phys. Rev. B **75**, 045315 (2007).
[11]Y. Tian, L. Ye, and X. F. Jin, Phys. Rev. Lett. **103**, 087206 (2009).
[12]K. M. Seemann, Y. Mokrousov, A. Aziz, J. Miguel, F. Kronast, W. Kuch, M. G. Blamire, A. T. Hindmarch, B. J. Hickey, I. Souza, and C. H. Marrows, Phys. Rev. Lett. **104**, 076402 (2010).
[13]J. A. Christodoulides, P. Farber, M. Daniil, H. Okumura, G. C. Hadjipanayis, V. Skumryev, A. Simopoulos, and D. Weller, IEEE Trans. Magn. **37**, 1292 (2001).
[14]J. Moritz, B. Rodmacq, S. Auffret, and B. Dieny, J. Phys. D: Appl. Phys. **41**, 135001 (2008).
[15]S. Okamoto, N. Kikuchi, O. Kitakami, T. Miyazaki, and Y. Shimada, Phys. Rev. B **66**, 024413 (2002).
[16]G. G. Lonzarich and L. Taillefer, J. Phys. C **18**, 4339 (1985).
[17]M. J. Otto, R. A. M. van Woerden, P. J. van der Valk, J. Wijngaard, C. F. van Bruggen, and C. Haas, J. Phys.: Condens. Matter **1**, 2351 (1989).
[18]I. Mannari, Prog. Theor. Phys. **22**, 335 (1959).
[19]N. Nagaosa, J. Sinova, S. Onoda, A. H. MacDonald, and N. P. Ong, Rev. Mod. Phys. **82**, 1539 (2010).
[20]N. Manyala, Y. Sidis, J. F. Ditusa, G. Aeppli, D. P. Young, and Z. Fisk, Nature Mater. **3**, 255 (2004).
[21]B. C. Sales, R. Y. Jin, D. Mandrus, and P. Khalifah, Phys. Rev. B **73**, 224435 (2006).
[22]A. Husmann and L. J. Singh, Phys. Rev. B **73**, 172417 (2006).
[23]Y. Onose and Y. Tokura, Phys. Rev. B **73**, 174421 (2006).
[24]M. Lee, Y. Onose, Y. Tokura, and N. P. Ong, Phys. Rev. B **75**, 172403 (2007).
[25]P. Nozières and C. Lewiner, J. Phys. (France) **34**, 901 (1973).
[26]J. Kötzler and W. Gil, Phys. Rev. B **72**, 060412 (2005).
[27]N. Jaouen, D. Babonneau, J. M. Tonnerre, D. Carbone, F. Wilhelm, A. Rogalev, T. K. Johal, and G. van der Laan, Phys. Rev. B **76**, 104421 (2007).
[28]C. Antoniak, J. Lindner, M. Spasova, D. Sudfeld, M. Acet, M. Farle, K. Fauth, U. Wiedwald, H. G. Boyen, P. Ziemann, F. Wilhelm, A. Rogalev, and S. H. Sun, Phys. Rev. Lett. **97**, 117201 (2006).
[29]B. M. Lairson and B. M. Clemens, Appl. Phys. Lett. **63**, 1438 (1993).
[30]T. Seki, Y. Hasegawa, S. Mitani, S. Takahashi, H. Imamura, S. Maekawa, J. Nitta, and K. Takanashi, Nature Mater. **7**, 125 (2008).