Thickness dependence of the anomalous Hall effect in disordered face-centered cubic FePt alloy films*

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The anomalous Hall effect in disordered face-centered cubic (fcc) FePt alloy films is experimentally studied. The longitudinal resistivity independent term of the anomalous Hall conductivity (AHC) increases and approaches saturation with increasing film thickness. The contribution of side jump scattering is suggested to decrease monotonically with increasing film thickness, which can be ascribed to the variation of the surface scattering with the film thickness. The sign of the skew scattering contribution to the AHC is opposite to that of the intrinsic contribution in the system.

Keywords: anomalous Hall effect, FePt, disordered alloy

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1. Introduction

The anomalous Hall effect (AHE),[1] which is proportional to the z component of magnetization in ferromagnetic materials, has received renewed interest in recent years.[1–21] The scaling law describing the anomalous Hall resistivity ρ_{AH} in terms of the longitudinal resistivity ρ_{xx} is empirically expressed as $\rho_{\mathrm{AH}} = a\rho_{xx} + b\rho_{xx}^2$. The linear term on the right side is known as the contribution from the skew scattering,[3] while the quadratic term is thought to arise from both the intrinsic[2] and side jump mechanisms.[4] The mechanism behind the complex phenomena of AHE is still poorly understood although it is closely connected to the spin Hall effect, which possesses a large potential for applications in the spintronic devices.[5]

Enormous attempts have been made recently to separate these contributions to the AHE both experimentally and theoretically.[6–20] In ferromagnetic systems of crystals, where the translational symmetry is kept, investigations on the intrinsic and extrinsic AHE in the conventional transition metal ferromagnets[6,7,13,18,19] and chemically ordered ferromagnetic alloys[9,14–17] have been extensively conducted recently. The intrinsic anomalous Hall conductivity (AHC) was calculated by an integration over the Fermi sea of the Berry curvature of each occupied band of Bloch states.[7,8] While in magnetic alloy systems, the extrinsic spin-dependent skew scattering and side jump due to asymmetric impurity scattering come to play important roles. For diluted and concentrated alloys, the occurrence of the AHE is primarily ascribed to extrinsic contributions.[3,4] Since the translational symmetry in disordered alloys is broken, calculations of the intrinsic AHC are therefore not possible on the basis of the Berry-phase curvatures. Lowitzer *et al.* reported a coherent description of the intrinsic and extrinsic AHE on an *ab initio* level for the disordered alloy systems of face-centered cubic (fcc) $\mathrm{Fe}_x\mathrm{Pd}_{1-x}$ and $\mathrm{Ni}_x\mathrm{Pd}_{1-x}$.[10] The chemical disorder has been accounted for by using the coherent potential approximation. The AHE was found to be dominated by the intrinsic as well as the skew scattering contributions.[10] Meanwhile, few attempts have been made to study the AHE experimentally in chemically disordered alloys.[10] In order to verify the validity of the calculations, more experimental investigations on disordered alloy systems are thus required. In this work, we report an experimental study of the AHE in disordered fcc $\mathrm{Fe}_{50}\mathrm{Pt}_{50}$ (FePt) films. We extract the intrinsic and side jump contributions to the AHC. The latter one can be tuned monotonically by varying the film thickness. These results provide well defined experimental data for future theoretical investigations.

2. Experiments

A series of disordered fcc FePt films with varying thicknesses were grown on MgO (001) substrates by direct current magnetron sputtering at room temperature. The base pressure of the sputtering chamber was below 3×10^{-6} Pa. The sputtering gas Ar with 99.999% purity was introduced with a constant pressure of 0.5 Pa. The deposition rate was about 0.1 nm/s. The microstructure and the film thickness were identified by x-ray diffraction (XRD) and x-ray reflectivity (XRR) using a D8 Discover x-ray diffractometer with Cu K_α source,

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respectively.[14,17] The films were patterned into normal Hall bars; the Hall resistivity ρ_H was measured from 50 K to 400 K. The longitudinal resistivity ρ_{xx} was measured simultaneously in the same temperature regime. Here ρ_H and ρ_{xx} were measured by a physical property measurement system (PPMS) from Quantum Design Inc. In experiments, the magnetoresistance of all samples was less than 1.0% and ρ_{xx} was taken at zero magnetic field. The spontaneous magnetization M_S was also measured as a function of temperature T by the PPMS.

3. Results and discussion

Deposited at ambient temperature, FePt films of all thicknesses are of the fcc crystal structure with (111) preferred orientation, as shown in the XRD results of Fig. 1. The FePt fcc (111) diffraction peaks, overlapped on the strong adjacent MgO (002) peaks, are still clearly observable, as indicated by the arrow. The peak near $2\theta = 38°$ comes from the MgO substrates. No indication of $L1_0$ ordering, like the fct (001) peak at about $2\theta = 24°$,[22] can be found in the diffraction pattern. It demonstrates the full chemical disorder in our samples and is consistent with the previous study on the T dependence of FePt ordering.[14,22] The same crystal structure and orientation of all samples enable us to study the thickness dependence of the AHE in the disordered FePt alloy films. Due to its crucial importance in the data analysis, the film thickness is accurately measured by XRR at small angles. The XRR results show that the film thicknesses fabricated in this study are around 30 nm, 40 nm, 50 nm, 70 nm and 100 nm.

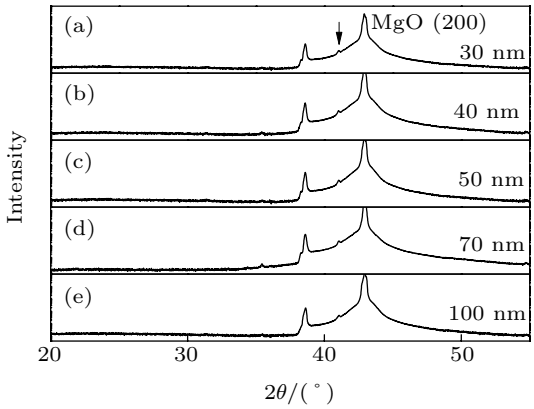


Fig. 1. XRD patterns for fcc disordered FePt films of different thicknesses ((a)–(e)). For clarification, the curves are shifted.

Figure 2(a) shows several representative Hall resistance R_H versus H curves measured between 50 K and 400 K for a 40-nm thick film. These curves are slanted before saturation, indicating an in-plane anisotropy. The saturation magnetic field H_s indicated by the dotted line increases monotonically as the temperature decreases because the demagnetization field becomes larger at low temperature, as shown below. The magnetocrystalline anisotropy may have a minor effect on the saturation magnetic field. For ferromagnetic films, the Hall resistance is $R_H = R_O H + 4\pi M R_S$, where R_O and R_S are the coefficients of the ordinary and the anomalous Hall effects, respectively. The anomalous Hall resistivity ρ_{AH} is obtained as the zero field extrapolation of the high field data, as shown in the Fig. 2(a).[6,19] The temperature dependence of ρ_{AH} is displayed in Fig. 2(b) for all thicknesses. Here, ρ_{AH} is found to increase monotonically with increasing T and decrease with increasing film thickness. The $\rho_{xx}(T)$, simultaneously measured, is shown in Fig. 2(c) for all samples. Here, ρ_{xx} shows the behavior of a normal metal, which increases with increasing T due to the increased phonon or spin flip scattering.[6,14] When the film thickness increases, ρ_{xx} at low temperature (55 K) decreases monotonically due to the finite size effect in electrical resistivity of thin metallic films.[18,19,23] By tuning the film thickness, the impurity density can be continuously manipulated. Meanwhile, the electronic structure experiences little alternation in the present thickness range. This finite size effect has been utilized to achieve an independent control of the extrinsic and intrinsic contributions to the AHE.[6,18,19] Overall, ρ_{xx} is greatly enhanced in disordered FePt films as compared with that in $L1_0$ ordered FePt films[14,17] as the chemical disorder in the investigated random substitutional alloys increases the electron scattering probability.

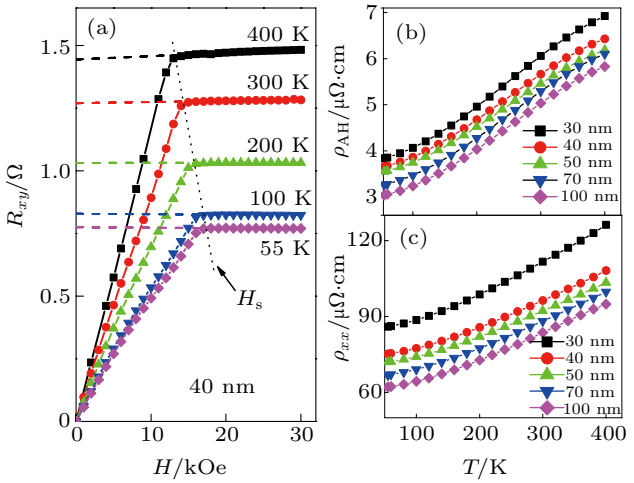


Fig. 2. (color online) (a) The R_{xy} versus H curves for a 40-nm film and (b) ρ_{AH}, (c) ρ_{xx} versus T for fcc disordered FePt alloy films of different thicknesses. The dashed line in panel (a) is a linear fit of high magnetic field data, which can be extrapolated to zero field to obtain the anomalous Hall resistance R_{AH}. The dotted line in panel (a) serves as a guide to the eye.

To extract different contributions to the AHE, the empirical scaling equation is used. In order to get the coefficients of a and b, the ρ_{AH}/ρ_{xx} ratio is plotted as a function of ρ_{xx} in Fig. 3(a). Clearly, the ρ_{AH}/ρ_{xx} ratio deviates gradually from the linear ρ_{xx} dependence with increasing ρ_{xx}. This deviation arises from our experimental strategy in which, for a given sample, the variation of ρ_{AH}/ρ_{xx} is accomplished by vary-

ing T. The varying T inevitably changes spontaneous magnetization M_S in the sample and the M_S related coefficients a and b.[14,17] As a result, a and b cannot be considered as constants as the M_S variation cannot be neglected in the measured T range. As shown in the inset of Fig. 3(a), M_S decreases with increasing T by about 23% when T rises from 50 K to 400 K. The $M_S(T)$ can be fitted by a linear function of T^2, arising from long-wavelength, low-frequency fluctuations of the magnetization or multiple excitations of the interacting spin waves.[24,25]

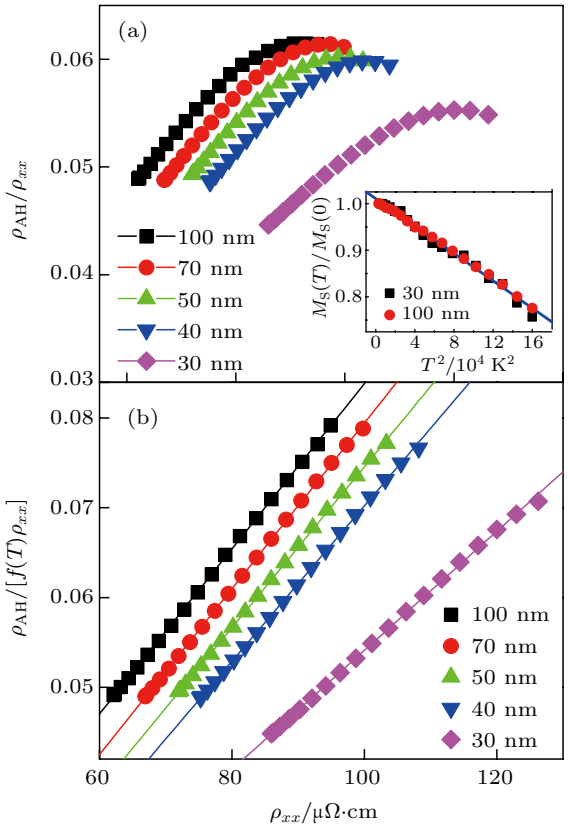


Fig. 3. (color online) The (a) ρ_{AH}/ρ_{xx} and (b) $\rho_{AH}/[\rho_{xx}f(T)]$ versus ρ_{xx} for fcc disordered FePt films of different thicknesses. The solid lines in panel (b) refer to linear fits. The inset shows the normalized spontaneous magnetization $M_S(T)/M_S(0)$ versus T^2 for 30-nm and 100-nm thick films; the solid line is a linear fit.

A modification of the conventional scaling law is considered in recent experimental studies[14,17] since the change of M_S cannot be neglected. Considering that the intrinsic AHC is proportional to M_S, we assume σ_{AH}^{int} and M_S having the same T dependence, i.e., $\sigma_{AH}^{int}(T) = \sigma_{AH}^{int0} f(T)$ and $M_S(T) = M_{S0} f(T)$.[24] Moreover, the skew scattering contribution σ_{AH}^{sk} is found to be roughly proportional to M_S.[26] Therefore, $a = a_0 f(T)$ and $b = b_0 f(T)$ are assumed, where a_0 and b_0 refer respectively to a and b at 0 K. The validity of the above assumption has been demonstrated previously[14,17] and is shown again in Fig. 3(b), where the $\rho_{AH}/[\rho_{xx}f(T)]$ ratio for all the samples is shown to be a perfect linear function of ρ_{xx}. The slope and the intercept of the lines are therefore b_0 and a_0, respectively. This shows that, to reliably deduce b_0 and a_0 for disordered fcc FePt films, it is also essential to take into account the T dependence of the M_S in the T regime studied.

The extracted a_0 and b_0 from the linear fitting in Fig. 3(b) are shown in Figs. 4(a) and 4(b), respectively. The b_0 increases monotonically with increasing film thickness, showing a dramatic change when the film thickness increases from 30 nm to 40 nm and a saturation when the film thickness is above 70 nm. Similar phenomena have been observed in epitaxial Co films and ultrathin fcc disordered FePt films.[19,21] For thick fcc FePt films, $b_0 = 920\ \Omega^{-1}\cdot\mathrm{cm}^{-1}$. This value is much smaller than that ($1800\ \Omega^{-1}\cdot\mathrm{cm}^{-1}$) of Fe films[6] and close to that of epitaxial Co films.[19] It is well known that b_0 contains both the extrinsic side jump (σ_{AH0}^{sj}) and the intrinsic (σ_{AH0}^{int}) contributions to the AHC, i.e., $b_0 = \sigma_{AH0}^{int} + \sigma_{AH0}^{sj}$.[9,14,17] Since the crystal structure and orientation are the same for all films, the intrinsic contribution σ_{AH0}^{int} should be the same as the band structure is preserved with little modification in the present thickness range.[6,18,19,23] The monotonical increase in b_0 with the film thickness cannot be explained with the variations of the electronic band structure. As the surface scattering effect decreases with increasing film thickness, the side jump contribution σ_{AH0}^{sj}, which arises from the surface scattering in the presence of the spin–obit coupling, should decrease in magnitude with increasing film thickness. Then we may infer that σ_{AH0}^{sj} approaches zero monotonically with increasing film thickness, as shown in Fig. 4(b), considering that σ_{AH0}^{int} equals to b_0 at thick (100 nm) films. For an identical film thickness, b_0 of the disordered FePt films is smaller than that of the ordered FePt films.[14,17] The present results also agree with the calculations of σ_{AH0}^{sj} in disordered Fe_xPd_{1-x}. While the skew scattering parameter a_0 shows a negative value and changes non-monotonically, which first increases then decreases in magnitude with increasing film thickness. The decreasing of the skew scattering contribution to the AHE with increasing film thickness has also been found in Fe and Co films.[6,23] Opposite signs of a_0 and b_0 in disordered FePt alloy films indicate that the skew scattering contributes to the AHC[10]

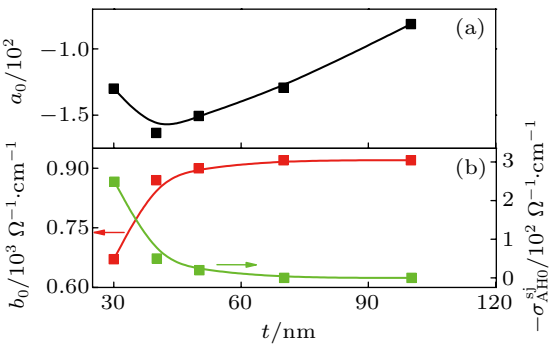


Fig. 4. (color online) The (a) a_0, (b) b_0 and σ_{AH0}^{sj} each as a function of the film thickness for disordered fcc FePt films. Solid lines serve as a guide to the eye.

in an opposite way to that of the intrinsic term, as also observed in body-centered cubic (bcc) Fe films.[6] These results will stimulate further theoretical investigations on the AHE in disordered ferromagnetic alloys, which are a large family of the ferromagnetic materials.

4. Conclusion

We have fabricated fcc disordered FePt films and studied the AHC as a function of the film thickness. It is demonstrated that b_0 increases with increasing film thickness and finally approaches a constant. It is suggested that the contribution of the side jump to the AHC becomes weak for thick films because the effect of the surface scattering becomes small in thick films. We also find that the skew scattering contribution to the AHC is opposite to that of the intrinsic term and becomes weak for thick FePt films. This work will be helpful to understand the mechanism of the AHC in 3d disordered magnetic alloys.

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