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Scaling of Anomalous Hall Effect in Amorphous CoFeB Films With Accompanying Quantum Correction

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ABSTRACT

Scaling of anomalous Hall effect in amorphous CoFeB films with thickness ranging from 2 to 160 nm have been investigated. We have found that the scaling relationship between longitudinal (ρ_{xx}) and anomalous Hall (ρ_{AH}) resistivity is distinctly different in the Bloch and localization regions. For ultrathin CoFeB films, the sheet resistance (R_{xx}) and anomalous Hall conductance (G_{AH}) received quantum correction from electron localization showing two different scaling relationships at different temperature regions. In contrast, the thicker films show a metallic conductance, which have only one scaling relationship in the entire temperature range. Furthermore, in the dirty regime of localization regions, an unconventional scaling relationship $\sigma_{AH} \propto \sigma_{xx}^{\alpha}$ with $\alpha=1.99$ is found, rather than $\alpha=1.60$ predicted by the unified theory.

Keywords: CoFeB; Anomalous Hall effect; Electron localization; Ultrathin films

I. INTRODUCTION

The anomalous Hall effect (AHE) in ferromagnetic materials has attracted extensive attention due to its controversial mechanisms [1] and potential applications in electronics devices [2]. The Hall resistivity ρ_{xy} can be given by an empirical relation of $\rho_{xy}=R_0B+4\pi R_sM$, where the first term is ordinary Hall resistivity due to Lorentz force, and the second term that is proportional to magnetization M refers to anomalous Hall resistivity ρ_{AH} . Current understanding on AHE is based on the side-jump [3], skew-scattering [4], and intrinsic mechanisms [5, 6]. The dependence between longitudinal resistivity ρ_{xx} and ρ_{AH} is usually taken to judge which mechanism dominates [1]. The skew-scattering and side-jump mechanisms yield $\rho_{AH} \propto \rho_{xx}$ and $\rho_{AH} \propto \rho_{xx}^2$, respectively. Intrinsic mechanism based on Berry phase of Bloch waves also gives $\rho_{AH} \propto \rho_{xx}^2$. Recently, a unified theory has been proposed based on the multiband ferromagnetic metals with diluted impurities taking on an equal footing both the intrinsic and extrinsic contributions [7-9]. It predicts that in the clean regime (longitudinal conductivity $\sigma_{xx}>10^6$ S/cm), AHE is dominated by skew-scattering (anomalous Hall conductivity $\sigma_{AH} \propto \sigma_{xx}$). In the disorder regime (10^4 S/cm $<\sigma_{xx}<10^6$ S/cm), the intrinsic contribution becomes dominant, resulting in $\sigma_{AH}=\text{const}$. In the dirty regime ($\sigma_{xx}<10^4$ S/cm), a scaling relation of $\sigma_{AH} \propto \sigma_{xx}^{1.6}$ is predicted, which is caused by the damping of intrinsic contribution. However, the unified theory does not take the quantum effect of Coulomb interaction and electron localization into account in the dirty regime.

At low temperatures, the physics of AHE is enriched by quantum effects of Coulomb interaction and electron localization [10-20]. The Coulomb interaction correction to anomalous Hall conductance G_{AH} has been found to vanish for both the skew-scattering and side-jump mechanisms [10, 11] due to general symmetry reasons [18]. Whereas, the electron localization correction to G_{AH} is nonzero for skew-scattering [12, 20] and vanishes for side-jump mechanism [18, 20]. The scaling exponent in the dirty regime has been found to become 2.0, rather than 1.6 that is predicted by the unified theory, when G_{AH} receives quantum corrections from Coulomb interaction [16] and electron localization [13]. However, the evolution of the scaling relationship in the presence of quantum effect of Coulomb interaction and/or electron localization is still poorly known.

Amorphous CoFeB films have been a subject of extensive studies due to its low coercivity, large saturation magnetization [21, 22] and high spin polarization [23], which were widely used in theory research [24, 25], magnetic tunnel junctions [26] and spin transfer torque devices [27]. The proper scaling of amorphous CoFeB in the dirty regime without consideration of the quantum correction can be explained by the combination of extrinsic and intrinsic mechanisms quantitatively [28]. It is also demonstrated that the G_{AH} of amorphous CoFeB received weak location correction [29]. However, the scaling of amorphous CoFeB with accompanying quantum correction is still unknown. In this paper, the scaling of AHE in amorphous CoFeB films with accompanying quantum correction is investigated. Our study demonstrates the electron localization correction to both sheet resistance R_{xx} and G_{AH} , and displays

the scaling relationship of ultrathin amorphous CoFeB films in both Bloch and localization regions.

II. EXPERIMENTAL DETAILS

Amorphous CoFeB films with different film thicknesses (t) were fabricated on glass and nature-oxidized Si(100) substrates at room temperature by dc facing-target sputtering from a pair of $\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}$ targets with a base pressure better than 2.0×10^{-5} Pa. The sputtering pressure was kept at 0.35 Pa with 100-sccm Ar gas. The film thickness was calibrated by sputtering time and rate. The sputtering rate was 0.044 nm/s determined by measuring the film thickness with Dektak 6M surface profiler and high-resolution transmission electron microscopy (TEM). The surface morphology was analyzed by atomic force microscopy (AFM). The microstructure was characterized using TEM. Hall bars were fabricated by using the shadow masks that have five terminals, which can be used to measure transverse and longitudinal resistances simultaneously. Patterned films on glass substrates were used for electrical transport and Hall effect measurements with a Quantum Design PPMS-9 under a magnetic field up to 5 T in the range of 5-375 K. In Hall effect measurements, the contribution from offset values and/or magnetoresistance were removed by subtracting $\rho_{xy}(H)$ from $\rho_{xy}(-H)$. The ρ_{AH} was obtained by extrapolating the high field data to zero field.

III. RESULTS AND DISCUSSION

Figs. 1(a)-(d) display AFM images of amorphous CoFeB films with $t=2, 5, 40$ and 160 nm deposited on nature-oxidized Si(100) substrates. The average surface roughness is $0.527, 0.314, 0.345$ and 0.416 nm respectively. All samples has smooth surface. Fig. 2(a) shows the cross-sectional high-resolution TEM image of amorphous CoFeB film with $t=160$ nm on nature-oxidized Si(100) substrate. The lattice fringes of Si substrate can be clearly observed, but no lattice fringes from CoFeB appear, suggesting that CoFeB layer is amorphous. The high-resolution TEM image of CoFeB layer is shown in Fig. 2(b), also clearly showing that the atoms are disordered in CoFeB layer. The insert of Fig. 2(b) is the selected-area electron diffraction patterns. From this insert, we can see that a broad halo from amorphous CoFeB appears and the other spot patterns come from single-crystal Si. The broad ring appears from randomly orientated small crystallites CoFe(110) and CoFe(211), indicating that the sample has only short-range order at the atomic length scale. From the bright-field HRTEM image and selected-area electron diffraction pattern, we can conclude that CoFeB film is amorphous.

Fig. 3(a) shows the sheet resistance $R_{xx}(T)$ of the films with different t . It is clear that R_{xx} increases with the increase of temperature at $t=40, 80$ and 160 nm, showing a metallic conductance. At $t \leq 4$ nm, the temperature-dependent R_{xx} indicates a semiconducting-like conductance. At $t=5$ nm, the film also shows a semiconducting-like characteristic at low temperatures. The inset in Fig. 3(a) shows

the R_{xx} - t curves of the films at 5 K. One can see that R_{xx} decreases with the increase of t , which can be attributed to the enhanced surface scattering due to the decreased t . The ρ_{xx} of $t=2$ nm is 1735.8 $\mu\Omega$ cm at room temperature, which is consistent with the reported values of amorphous CoFeB film [21, 23]. Fig. 3(b) shows the normalized R_{xx} - $\ln T$ curves at $t=3, 4$ and 5 nm. At the low-temperature region, R_{xx} shows a linear $\ln T$ dependence. This phenomenon can be attributed to the two-dimensional weak electron localization and/or Coulomb interaction [30]. At $t=2$ nm, R_{xx} increases faster than $\ln T$. This transportation is expected to be of a variable range hopping mechanism, which satisfies the relation of

$$R_{xx}(T) = C \exp[(T''/T)^\beta] \quad (1)$$

where $R_{xx}(T)$ is sheet resistance and β depends on whether the hopping process between strongly localized states is influenced by Coulomb interaction. $\beta=1/3$ and $1/2$ correspond to Mott's variable range hopping process [31] and the role of Coulomb correlations [32] in two-dimensional systems, respectively. $\beta=1/4$ corresponds to Mott's variable hopping process in three-dimensional systems [31]. Fig. 3(c) shows the $\ln(R_{xx})$ as a function of $T^{-1/3}$ at $t=2$ nm. The experimental data can be well fitted in the temperature range of 5-30 K by using Eq. (1) with $\beta=1/3$. We have also fitted the data using $\beta=1/2$ and $1/4$ (not shown). However, the discrepancy becomes obvious above 10 K. The fitted results suggest that the quantum correction to R_{xx} is mainly from electron localization from 5 to 30 K.

Fig. 4 shows the field dependence of ρ_{xy} and magnetization for $t=2$ and 40 nm films at different temperatures. The field-dependent ρ_{xy} curves are very similar with the field-dependent magnetization curves, which is consistent with the AHE empirical relation. With the applied field increasing, the magnetization is forced to rotate to the field direction gradually, which results in a linearly field-dependent magnetization until saturation. The magnetization of $t=2$ nm is nearly 1000 emu/cm³, which is much larger than that of magnetite (400 emu/cm³), indicating the nature properties of amorphous CoFeB film [21, 33]. The saturation magnetic field of $t=40$ nm is larger than that of $t=2$ nm. The behavior of magnetization curves is typical for soft ferromagnetic film whose magnetization lies in the film plane when the field is applied perpendicularly to the film plane. No hysteretic behavior was observed for either sample.

In Fig. 5(a) we plot $\ln\rho_{AH}$ of the film with $t=2$ nm as a function of $T^{1/3}$. It displays $\ln(\rho_{AH})\sim T^{1/3}$ tendencies at low temperatures, which is similar to its R_{xx} vs T behavior, as shown in Fig. 3(c). Fig. 5(b) shows the dependence of ρ_{AH} on $\ln T$ at $t=3, 4$ and 5 nm. A relationship of $\rho_{AH}\sim\ln T$ is also found at low temperatures, which shows the same trend with $R_{xx}(T)$. The $\rho_{AH}(T)$ of the ultrathin CoFeB films displays the $\rho_{AH}\sim\ln T$ and/or $\ln(\rho_{AH})\sim T^{1/3}$ relationships at low temperatures, indicating the quantum corrections to ρ_{AH} [13, 15], which will be discussed in details next.

We now focus on the quantum correction to G_{AH} in amorphous CoFeB films. “Normalized relative change” $\Delta^N(Q_{ij})=(1/L_0R_0)(\delta Q_{ij}/Q_{ij})$ has been defined [12], where $L_0=e^2/\pi h$, R_0 is the sheet resistance at $T_0=5$ K, $\delta Q_{ij}=Q_{ij}(T)-Q_{ij}(T_0)$ and Q_{ij} refers to

resistance R_{xx} , R_{AH} or conductance G_{xx} , G_{AH} . Following Bergman and Ye's notation [10],

$\Delta^N R_{xx}$, $\Delta^N G_{xx}$, $\Delta^N R_{AH}$ and $\Delta^N G_{AH}$ can be expressed as

$$\Delta^N(R_{xx}) = \frac{1}{L_{00}R_0} \frac{\delta R_{xx}}{R_{xx}} = -A_R \ln \frac{T}{T_0} \quad (2)$$

$$\Delta^N(R_{AH}) = \frac{1}{L_{00}R_0} \frac{\delta R_{AH}}{R_{AH}} = -A_{AH} \ln \frac{T}{T_0} \quad (3)$$

for the facts that $|\delta R_{xx}| \ll R_0$, and $R_{AH}(T) \ll R_{xx}(T)$ for our films, we have

$G_{xx} \approx 1/R_{xx}$, $G_{AH} \approx R_{AH} / R_{xx}^2$, so $\Delta^N G_{xx}$ and $\Delta^N G_{AH}$ can be deduced as

$$\Delta^N(G_{xx}) = A_R \ln \frac{T}{T_0} \quad (4)$$

$$\Delta^N(G_{AH}) = (2A_R - A_{AH}) \ln \frac{T}{T_0} = A_{xy} \ln \frac{T}{T_0} \quad (5)$$

According to Muttalib and Wölfle's report [18], Coulomb interaction and weak electron localization correction to G_{xx} leading to a logarithmic temperature dependence are $\delta G_{xx}^{CI} = (e^2 / \pi h) h_{xx} \ln(T / T_0)$ and $\delta G_{xx}^{EL} = (e^2 / \pi h) \ln(T / T_0)$ respectively, where h_{xx} is the exchange plus Hartree interaction contribution to G_{xx} .

As a result, $\Delta^N G_{xx}$ can be deduced as [18]

$$\Delta^N G_{xx} = (1 + h_{xx}) \ln(T/T_0). \quad (6)$$

Figs. 6(a)-(d) show $\Delta^N R_{xx}$, $\Delta^N R_{AH}$ and $\Delta^N G_{AH}$ of the films with $t=2, 3, 4$ and 5 nm as a function of temperature. We can see that the data can be linearly fitted well with $\ln T$ below 30 K. The prefactors A_R for the films with $t=3, 4, 5$ nm are almost 1 . The result suggests that the Coulomb interaction correction to G_{xx} can be negligible according to Eq. (6). On the other hand, we have also calculated the slope of G_{xx} as a function of $\ln T$ below 30 K at $t=3, 4$ and 5 nm, respectively. All the slopes are 1.2×10^{-5} S, which confirmed that Coulomb interaction correction to G_{xx} is insignificant again [13, 15]. The inset in Fig. 3(b) shows the $G_{xx}-\ln T$ curves for the representative film with $t=5$ nm. The prefactors of $\Delta^N G_{AH}$, namely A_{xy} , are far from zero at $t=2, 3$ and 4 nm. It should be noted that both calculation [18] and experimental [12] results have demonstrated that there was no interaction-induced $\ln T$ correction to G_{AH} . The nonzero prefactors A_{xy} suggesting that the weak electron localization correction to G_{AH} is present. The smaller coefficients A_R and A_{AH} at $t=2$ nm can be attributed to its large R_{xx} at 5 K [12, 14]. In contrast, a universal scaling $2A_R \approx A_{AH}$ is observed at $t=5$ nm, indicating that the quantum correction to G_{AH} is negligible. The calculations to quantum correction to G_{AH} have shown that the electron localization contribution from side-jump model is absent [20]. Our observations are consistent with the side-jump mechanism. The absence of quantum correction to G_{AH} was also found in amorphous Fe [10] and metallic GaMnAs films [17].

With the well-confirmed electron localization correction to AHE in ultrathin

amorphous CoFeB films at low temperatures, the scaling of ultrathin films is investigated. The scaling relationship of $\rho_{AH}/\rho_{xx}=a+b\rho_{xx}$ at $t=2$ nm is plotted in Fig. 7(a). From the linear fitting, we can obtain $a=3.8\times10^{-3}$ and $b=-0.71$ S/cm at low temperatures, rather than $a=-1.8\times10^{-3}$ and $b=2.33$ S/cm at high temperatures. With the increase of temperature, the slope of the scaling changes from negative to positive. The sign change of the slope suggests that two distinct mechanisms in AHE may exist at different temperature regions. The scaling of the film with $t=5$ nm is shown in Fig. 5(b). Although the quantum correction to G_{AH} is absent, ρ_{xx} and ρ_{AH} receive quantum correction from weak electron localization at $t=5$ nm. The linear fitting yields $a=2.1\times10^{-3}$ and $b=99.25$ S/cm below 30 K, but $a=-7.1\times10^{-3}$ and $b=147.43$ S/cm at high-temperature region. The result demonstrates that there are also two different scaling at $t=5$ nm. It should be noted that the scaling at low temperatures is in the localization regions. For a comparison, we plot the scaling relationship of the film with $t=80$ nm without quantum correction at low temperatures as shown in Fig. 7(c). The only one linear fitting result from low temperature to room temperature yields $a=4.5\times10^{-4}$ and $b=153.24$ S/cm. Our results suggest that the anomaly of scaling in the ultrathin CoFeB films with $t\leq 5$ nm should be attributed to quantum correction from electron localization.

Finally, we turn our attention to the dirty regime of low conductivity $\sigma_{xx}<10^4$ S/cm, where an unconventional scaling relationship $\sigma_{AH} \propto \sigma_{xx}^2$ has been reported in ultrathin disordered CNI_3 films [16] and polycrystalline FePt films [13]. The Coulomb interaction and/or electron localization were suggested to play an important role in

the unconventional scaling exponent [13, 16]. Fig. 7(d) shows the $\sigma_{AH}-\sigma_{xx}$ relationship of the amorphous CoFeB films with $t=2-160$ nm below 30 K. We have fitted the data (dashed line) of the films with $t=2, 3$ and 4 nm with well electron localization correction to G_{AH} to $\sigma_{AH}=\text{const } \sigma_{xx}^{\alpha}$, and yields $\alpha=1.99$, which is similar with the unconventional scaling exponent $\alpha=2.00$. However, the fitting result (solid line) is 1.52 for the films with $t=40, 80$ and 160 nm without quantum correction at low temperatures, which is nearly to 1.60 predicted by the unified theory [7]. The unconventional scaling relationship in amorphous CoFeB films should also be attributed to electron localization correction to G_{AH} . Our study on the scaling of AHE in amorphous CoFeB films with accompanying quantum correction has enriched the physics of AHE. Especially, the anomaly of scaling in the localization regions confirmed the crucial role of quantum correction, which should be taken into account in the origin of AHE mechanism.

IV. CONCLUSION

In conclusion, we have carried out a systematic study on the electronic transport properties of amorphous CoFeB films. The logarithmic temperature dependence of both ρ_{xx} and ρ_{AH} are observed in ultrathin CoFeB films due to electron localization. The ultrathin films show two distinct scaling relationships at low- and high-temperature regions, which can be attributed to electron localization correction at low temperatures. We have also found an unconventional relationship

$\sigma_{AH} \propto \sigma_{xx}^{1.99}$ in the dirty regime of localization regions, which can be attributed to the electron localization correction to G_{AH} in ultrathin CoFeB films. Our results strongly suggest that the quantum correction plays an important role in the scaling of AHE in amorphous CoFeB films. However, the evolution of the scaling need to be theoretical studied with the presence of quantum effect of Coulomb interaction and/or electron localization.

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FIGURE CAPTIONS

Fig. 1. AFM images of amorphous CoFeB films with various thicknesses: (a) $t=2$ nm, (b) $t=5$ nm, (c) $t=40$ nm, (d) $t=160$ nm.

Fig. 2. (a) High-resolution cross-section TEM image of CoFeB film on Si(100) substrate; (b) High-resolution TEM image of CoFeB film, the inset is the selected-area electron diffraction patterns.

Fig. 3. (a) The normalized R_{xx} - T curves of amorphous CoFeB films with various t . Insert: $\ln$ scale of R_{xx} as a function of t at 5 K; (b) Normalized R_{xx} as a function of $\ln T$ at $t=3, 4$ and 5 nm. The inset is G_{xx} versus $\ln T$ at $t=5$ nm; (c) $\ln R_{xx} T^{-1/3}$ curve at $t=2$ nm. The inset is the $\ln R_{xx} T^{-1/2}$ curve at $t=2$ nm.

Fig. 4. Field-dependent ρ_{xy} at different temperatures for (a) $t=2$ nm, (b) $t=40$ nm. Field-dependent magnetization at different temperatures for (a) $t=2$ nm, (b) $t=40$ nm.

Fig. 5. (a) $\ln \rho_{AH}$ as a function of $T^{-1/3}$ at $t=2$ nm; (b) ρ_{AH} versus $\ln T$ curves at $t=4$ nm. Insets: Right $t=5$ nm, Left $t=3$ nm.

Fig. 6. $\ln$ scale of T dependence of $\Delta^N R_{xx}$, $\Delta^N R_{AH}$ and $\Delta^N G_{AH}$ at $t=(a) 2$ nm, (b) 3 nm, (c)

4 nm, (d) 5 nm. The solid straight lines are linearly fitted results below 30 K.

Fig. 7. (a)-(c) ρ_{AH}/ρ_{xx} versus ρ_{xx} curves are given by the dots, the red line is the linearly fitted by $\rho_{AH}/\rho_{xx}=a+b\rho_{xx}$, at t =(a) 2 nm, (b) 5 nm, (c) 80 nm; (d) The σ_{AH} as a function of σ_{xx} at t =2-160 nm below 30 K. The dashed line represents the fitted result to the experimental data at t =2, 3 and 4 nm. The solid line corresponds to the fitted results at t =40, 80 and 160 nm.

Highlights

- For ultrathin films, two different scaling at different temperature regions appear.
- The thicker films show a metallic conductance and only one scaling in the entire temperature range.
- In dirty regime, an unconventional scaling relation is $\sigma_{AH} \propto \sigma_{xx}^{\alpha}$ with $\alpha=1.99$.

Fig. 1

Fig. 2

Figure 3

Figure 4

Figure 5

Figure 6