Scaling of the anomalous Hall effect in ferrimagnetic $Co_{90}Gd_{10}$ thin films

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Abstract

We investigated the anomalous Hall effect and longitudinal magnetoresistance in ferrimagnetic $Co_{90}Gd_{10}$ thin films with thicknesses from 5 to 35 nm and temperatures from 80 to 300 K. As the temperature increases from 80 to 300 K, the saturation magnetization of $Co_{90}Gd_{10}$ increases from 720 to 844 emu/cm^3. However, the scaling law $\sigma_{xy} \sim \sigma_{xx}^n$ with n = 2.3 holds surprisingly well. Our results indicate that the scaling law usually reported in ferromagnetic materials remains valid for ferrimagnetic materials, which undoubtedly suggested the universality of the scaling law.

Key words: Scaling law, Ferrimagnet, anomalous Hall effect, Magnetoresistance.

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I. INTRODUCTION

The anomalous Hall effect (AHE) in ferromagnetic materials has attracted much attention for more than a century due to its physical complexity and important applications [1-10]. It tells us that electrons will acquire a spin dependent transverse velocity when moving through a magnetized ferromagnetic conductor. For different spin orientations, electrons are deflected towards their opposite directions. Thus, the nonzero spin polarization in ferromagnetic materials directly leads to a net transverse Hall voltage. In general, in ferromagnetic materials the anomalous Hall resistivity ρ_{xy} strongly depends on the material's magnetization. They are usually described in the empirical relation [1] as

$$\rho_{xy} = \mu_0 R_0 H + \mu_0 R_S M, \qquad (1)$$

where μ_0 is the vacuum magnetic permeability, H is the applied magnetic field, M is the magnetization, R_o and R_S are the ordinary and anomalous Hall coefficients, respectively. The first term on the right side of Eq. (1) describes the ordinary Hall effect, which is caused by the Lorentz force acting on the moving charged carriers. The second term represents the AHE, usually much larger than the first one [11].

Although AHE of ferromagnetic materials has been extensively studied, the origin of AHE has still been an intriguing but controversial issue. Nowadays this effect has been explained by three typical mechanisms: intrinsic contributions [3, 12, 13], skew scattering [14], and side jump [15]. In experiment, the detailed relation between ρ_{xy} and the longitudinal resistivity ρ_{xx} are dominated by their underlying mechanisms [16-19]. The intrinsic contributions is proposed by Karplus and Luttinger, which is a pure quantum effect [3]. It theoretically pointed out that AHE was related to the spin-orbit coupling in Bloch bands in a perfect ferromagnetic crystal. Recently such an intrinsic contribution has been expressed by a momentum-space Berry phase linked to the electronic structure of the multiband spin-orbit coupled system [20]. For this intrinsic contributions, $\rho_{xy} \sim \rho_{xx}^2$ is followed. The skew scattering is proposed by Smit [14]. In this theory, the spin-orbit coupling results in an effective magnetic field gradient within the scattering plan, exhibiting a spin-dependent scattering with different final momentum directions for spin-up and spin-down. In this case, the anomalous Hall resistivity linearly depends on the longitudinal resistivity, namely $\rho_{xy} \sim \rho_{xx}$. Finally, the side jump, proposed by Berger, is due to a spin-dependent-difference in electron acceleration and deceleration processes during the scattering, which effectively leads to a spin-dependent sideway displacement upon repeated scattering [15]. In experiment the side jump scattering mechanism gives the same scaling relation as the intrinsic contributions. By changing the temperature and the density of states at the Fermi surface, the power law relationship between ρ_{xy} and ρ_{xx} has been extensively studied experimentally in a large series of ferromagnetic materials [16, 20-22]. However, the scaling law of AHE is still lacking for ferrimagnetic materials, which includes two sets of magnetic lattices.

As a typical ferrimagnet, the magnetization of CoGd thin films can be controlled through modifying the alloy composition. When Gd contributes larger magnetization than that of Co, the magnetization of Co is antiparallel to that of CoGd thin films, and vice versa.

In this work, we systematically investigated the magnetic and transport properties (Hall and longitudinal magnetoresistance) of ferrimagnetic $Co_{90}Gd_{10}$ by changing the thicknesses from 5 to 35 nm. We showed that the saturation magnetization of $Co_{90}Gd_{10}$ is enhanced by 14% when the temperature increases from 80 to 300 K. Surprisingly, the scaling law $\sigma_{xy} \sim \sigma_{xx}^n$ with $n = 2.3$ still holds regardless of thickness and temperature, in a good agreement with the universal scaling law reported in ferromagnetic materials.

II. EXPERIMENTAL DETAILS

The sample of $Co_{90}Gd_{10}$ was deposited on Si (100) at ambient temperature by magnetron sputtering system. The compositions of $Co_{90}Gd_{10}$ layers were analyzed by Energy Dispersive X-ray Spectroscope (EDS). Structural characterization was carried out by X-Ray Diffraction (XRD). Here all $Co_{90}Gd_{10}$ films are amorphous (not shown for brevity). To analyze the magnetic properties, magnetization was measured by Vibrating Sample Magnetometer (VSM). The transport properties of samples were measured by current source (Keithley 220) and voltagemeter (Keithley 2182).

III. RESULTS AND DISCUSSION

Figure 1(a) shows the typical in-plane hysteresis loops for $Co_{90}Gd_{10}$ at room temperature (RT). The coercivity of $Co_{90}Gd_{10}$ is only about 27 Oe. For $\theta = 0$ and 90°, a weak anisotropy is observed due to the amorphous structure, where θ is the in-plane angle between the easy axis and magnetic field. Figure 1(b) shows the saturation magnetization (M_S) of $Co_{90}Gd_{10}$ as a function of temperature. As expected, the M_S of $Co_{90}Gd_{10}$ can be tuned significantly by changing the temperature. When temperature increases from 80 to 300 K, the M_S of $Co_{90}Gd_{10}$ also significantly increases from 720 to 850 emu/ cm^3, as shown in the inset of Fig. 1 (b). Remarkably, this temperature in dependence of M_S of $Co_{90}Gd_{10}$ contrasts to that of ferromagnet (e.g. Co, Fe, FeNi etc.), in which M_S almost keeps constant in the temperature range from 80 to 300 K. The distinctive temperature behavior of $Co_{90}Gd_{10}$ can be explained by the difference between the antiparallel Co and Gd magnetic moments. As the temperature further increases and is close to 700 K, which reaches the Curie temperature of $Co_{90}Gd_{10}$, the MS of $Co_{90}Gd_{10}$ sharply declines to zero. One can also notice a peak at T= 580 K in Fig. 1 (b), which might be caused by the crystallization in part of $Co_{90}Gd_{10}$.

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Similar to ferromagnetic materials anisotropy magnetoresistance (AMR) of $Co_{90}Gd_{10}$ at φ = 0 and 90° is shown in Fig. 2(a), where φ is the angle between the current and magnetic field in plane. In order to further confirm the AMR of $Co_{90}Gd_{10}$, we measured the angular in dependence of resistivity curves, where a specified magnetic field at 800 Oe is chosen to saturate the magnetization of $Co_{90}Gd_{10}$. It shows that the resistivity as a function of angle φ can be fitted well by cos2 (φ), as shown as the solid line in Fig. 2 (b). The cos2 (φ) angular dependence is consistent with the AMR observed in the ferromagnetic materials due to the spin-orbit coupling. However, one can also find that the MR ratio here is extremely low (only about 0.08%), due to the weak scattering of Gd magnetic moment, where the 4f magnetic moment of Gd atoms is far away the Femi surface. The weak AMR effect of $Co_{90}Gd_{10}$ also indicates that the magnetic scattering almost has no contribution to the longitudinal resistivity of $Co_{90}Gd_{10}$. We noticed a difference for the ρ_{xx} at $\varphi = \pm 90$. This might be caused by the sample is tilted against the magnet. Figure. 2 (c) shows the resistivity of $Co_{90}Gd_{10}$ as a function of temperature from 80 to 280 K. For all the thicknesses of $Co_{90}Gd_{10}$ the resistivity is largest at 280 K and gradually decays with the decreasing temperature. But below 180 K a linear decrease of resistivity is observed. The two types of temperature dependence indicate the competition scattering mechanisms. For the temperature range from 80 to 180K the magnetic scattering dominants the longitudinal resistivity. For the temperature above 180 K, the impurity scattering plays an important role in resistivity. Interestingly, the longitudinal resistivity is almost independent with the temperature for all thicknesses, despite the magnetization of $Co_{90}Gd_{10}$ can be tuned 14%.

The transverse Hall resistivities for all thicknesses from 5 to 35nm were measured at temperatures with range from 80 to 300K with the magnetic field applied perpendicular to the sample plane. Figure 3(a) shows the magnetic field dependence of the Hall resistivity at RT. The magnetization is saturated until the magnetic field reaches about 1.0 T. Above the saturation field, a weak linear increase of Hall resistivity is caused by the ordinary Hall effect. One can also find that the transverse Hall resistivity strongly depends on the thicknesses. It obviously increases with the increasing thicknesses. Remarkably, the Hall resistivity of $Co_{90}Gd_{10}$ increases upon increasing the thickness, whereas in ferromagnetic materials the Hall resistivity decreases with the thickness [19]. Figure 3 (c) shows the Hall resistivities of $Co_{90}Gd_{10}$ as a function of temperature from 80 to 280K for different thicknesses. Surprisingly, similar to the longitudinal resistivity, it can be seen that these values of anomalous Hall resistivity are weakly related to temperatures.

The longitudinal conductivity σ_{xx} and the transverse anomalous conductivity σ_{xy} were estimated through the relations $\sigma_{xx} = \rho_{xx} / (\rho_{xx}^2 + \rho_{xy}^2)$ and $\sigma_{xy} = \rho_{xy} / (\rho_{xx}^2 + \rho_{xy}^2)$, respectively, which can be approximated as $\sigma_{xx} \cong 1 / \rho_{xx}$ and $\sigma_{xy} \cong \rho_{xy} / \rho_{xx}^2$ in the different $Co_{90}Gd_{10}$ thicknesses because the absolute value of $\rho_{xy} \ll \rho_{xx}$.The relationship between σ_{xx} and σ_{xy} of $Co_{90}Gd_{10}$ has been concluded in Fig. 4. Due to $\sigma_{xx} < 10^4$ S/cm , our results can be considered to belong in the dirty limit region, where the relation $\sigma_{xy} \sim \sigma_{xx}^n$ with $n \cong 2$ is reported in ferromagnet [16]. By fitting all our data the value of $n = 2.3$ is obtained, which is also consistant with the results in ferromagnetic mateirals.

IV. CONCLUSIONS

In conclusion, we studied the scaling law of the ferrimagnet $Co_{90}Gd_{10}$, by setting various thicknesses and temperatures as control parameters to tune both σ_{xx} and σ_{xy}. The scaling law $\sigma_{xy} \sim \sigma_{xx}^n$ with $n = 2.3$ surprisingly holds in reasonable agreement with theory, which further confirms the universality of the scaling law. Our results also indicate that the AHE in $Co_{90}Gd_{10}$ is belong in the dirty limit region due to the doping.

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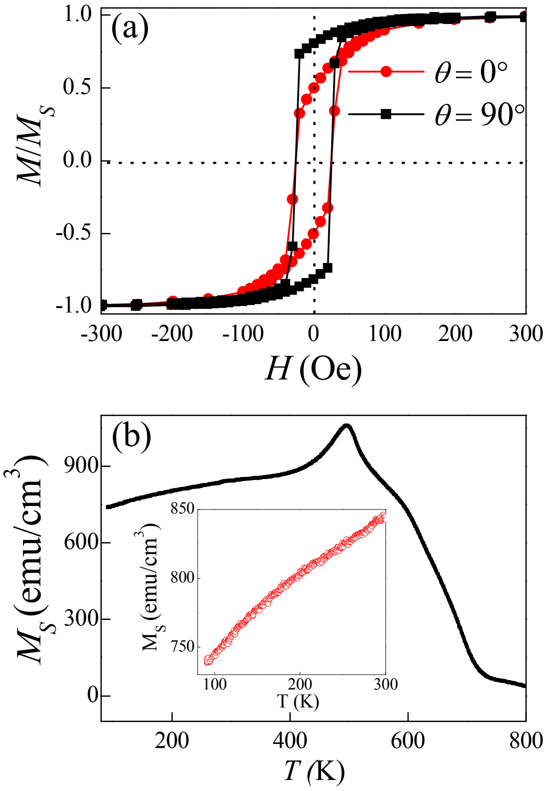

Fig. 1. (Color online) (a) The in-plane hysteresis loops of $Co_{90}Gd_{10}$ at RT with $\theta = 0$ and 90°, where θ is the in-plane angle between the easy axis and magnetic field. (b) The saturation magnetization M_S of $Co_{90}Gd_{10}$ as a function of temperature. The inset shows the temperature dependent M_S zooming in from 80 to 300 K.

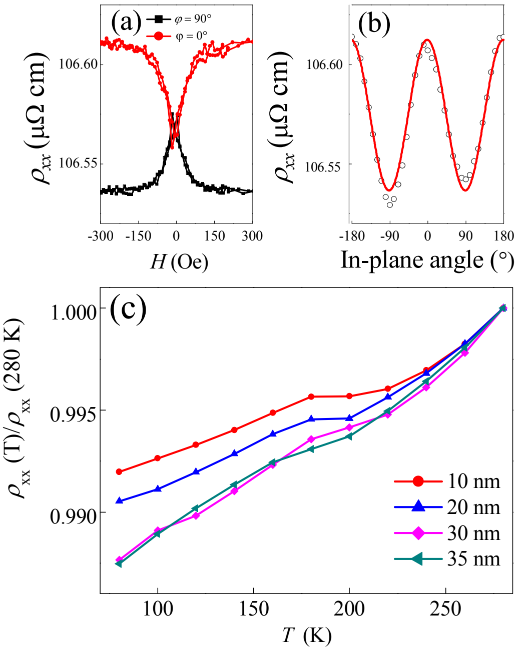

Fig. 2 (color online) (a) The longitudinal magnetoresistance of $Co_{90}Gd_{10}$ at RT for $\varphi = 0$ and 90^{o}, where φ is the angle between the current and magnetic field in plane. (b) The angular dependence of magnetoresistance of $Co_{90}Gd_{10}$ at RT. (c) Temperature dependence of longitudinal resistance of $Co_{90}Gd_{10}$ with different thicknesses.

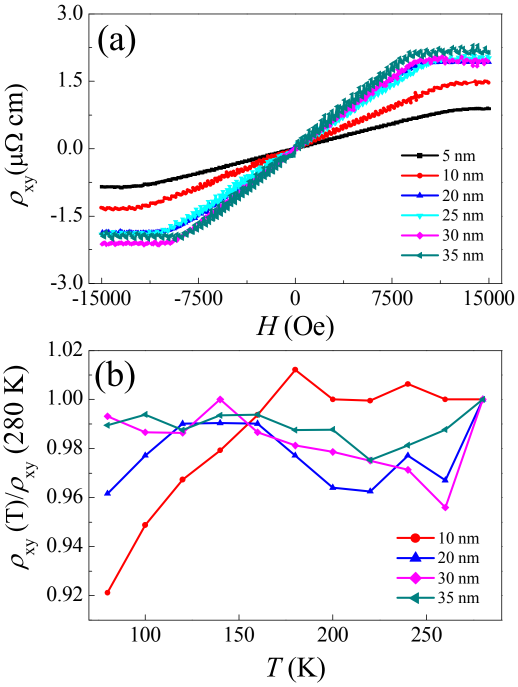

Fig. 3 (color online) (a) The Hall resistance of $Co_{90}Gd_{10}$ as a function of the magnetic field measured at RT with different thicknesses. (b) The temperature-dependent of Hall resistance for different thicknesses $Co_{90}Gd_{10}$.

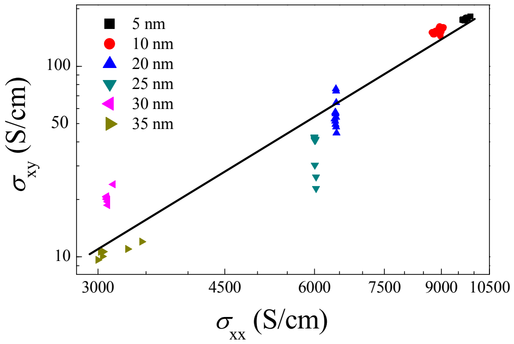

Fig. 4 (color online) Anomalous Hall conductivity σ_{xy} as a function of longitudinal conductivity σ_{xx} for $Co_{90}Gd_{10}$. The solid lines is fit to $\sigma_{xy} \sim \sigma_{xx}^{2.3}$.