Large extraordinary Hall effect in $[Pt/Co]_5/Ru/[Co/Pt]_5$ multilayers

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This Brief Report presents giant extraordinary Hall effect (EHE) in the Ru-mediated antiferromagnetically coupled $[Pt/Co]_5/Ru/[Co/Pt]_5$ multilayers (MLs) compared with those MLs without the Ru spacer. The enhancement of the EHE is attributed to the strong Ru/Co interface scattering. Through the variation in the Pt layer thickness and the temperature, we determine the relation between the Hall voltage and the longitudinal resistivity. It is found that the conventional scaling analysis has difficulties in consistently interpreting our data.

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I. INTRODUCTION

The physics of extraordinary Hall effect (EHE) has been well understood from the skew scattering theory proposed by Smit[1] and the anomalous velocity contribution studied by Karplus and Luttinger.[2] Both mechanisms originate from the spin-orbit coupling. Much of recent theoretical studies have been focused on alternative descriptions of the EHE phenomenon such as Berry phases[3] and spin Hall effects,[4,5] but the essential physics remains the same. From the experimental point of view, the quantitative description of the EHE is rather complex for different structures, in particular, for inhomogeneous systems such as magnetic multilayers (MLs) and granular films. More importantly, it is desirable to engineer magnetic structure which displays a large EHE for application in data storage. The Co/Pt multilayer system is particularly interesting because this system is a promising candidate for application in magnetic media and is known to have large EHE.[6] In this Brief Report, we report that much larger EHE can be observed for two Pt/Co MLs antiferromagnetically coupled via a Ru thin layer.

The Hall resistivity ρ_{xy} in a magnetic system is usually written as

$$\rho_{xy} = (V_{xy}/I_{xx})t = R_o H + R_e M, \tag{1}$$

where I_{xx} is the in-plane longitudinal current, V_{xy} is the transverse voltage drop in the plane of the layers, t is the film thickness, H is the applied magnetic field, R_o and R_e are the ordinary and extraordinary Hall coefficients, and M is the magnetization perpendicular to the film. The ordinary Hall coefficient from the Lorentz force on the conduction electron is rather small in diffusive metallic ferromagnets such as transition metals at room temperature and one can neglect it in the analysis of the EHE. While the spin-orbit coupling is responsible for the R_e, two specific contributions, skew scattering and anomalous velocity (side jump in the case of impurity-dominated anomalous velocity[7]), have a simple scaling relation between R_e and the longitudinal resistivity ρ_{xx} given below,

$$R_e = a\rho_{xx} + b\rho_{xx}^2, \tag{2}$$

where the first term comes from the skew scattering and the second term results from the anomalous velocity. Conventionally, the parameters (a and b) are experimentally determined by fitting the above equation via the temperature dependence of the resistivity. For a single layer or homogeneous sample, Eq. (2) fits experimental data rather well.[8] When the system is not a homogeneous ferromagnet, for example, magnetic MLs and granular films, the above scaling relation might fail. This is because the scattering at the interface and in the bulk of the layers contributes to the EHE and to the resistivity in a different way. Even if R_e could be written as the scaling relation of Eq. (2) for interface and bulk scattering separately, the total or measured R_e could take quite different scaling forms, depends on the layer thickness and the mean-free paths.[9] For example, $R_e \propto \rho^{3.5}$ had been reported in Co/Cu granular films.[10] In spite of these limitations, Eq. (2) remains approximately valid for several important layered systems, such as Co/Pt MLs. The experimental fitting to Eq. (2) may qualitatively determine the relative importance of the skew scattering and the anomalous velocity.[6,10,11]

In the present Brief Report, we consider Co(CoFe)/Pt MLs which display a strong perpendicular anisotropy. Currently, Co/Pt MLs are promising candidate materials for applications in perpendicular magnetic media[12] and sensors.[13,14] We insert a thin Ru layer between two Co/Pt MLs. The Ru layer plays two important roles for our EHE measurement. First, the Ru layer whose thickness is about 0.8 nm leads to a strong antiferromagnetical (AF) coupling between two Co/Pt MLs.[15] This strong coupling stabilizes each Co/Pt ML in a single-domain state, i.e., one can model the magnetic hysteresis by simple uniform rotation rather than domain-wall nucleation and propagation.[16,17] Thus, the magnetic states at any applied magnetic field can be readily identified and the EHE data can be analyzed without ambiguous domain patterns. Second, the Ru layer introduces two Ru/Co interfaces. The strong spin-dependent interface scattering has been known to affect the resistivity and magnetoresistance,[15] but the role of the Ru/Co interface on the EHE has not been well studied. Through the experimental variation in the layer thickness and the temperature, we determine the Hall resistivity and compare with earlier results[6] without Ru spacer. Among other things, we find that the Ru layer promotes a much larger Hall angle. The detail analysis of the scaling relation produces quite different pictures for layer thickness and temperature-controlled resistivity scalings.

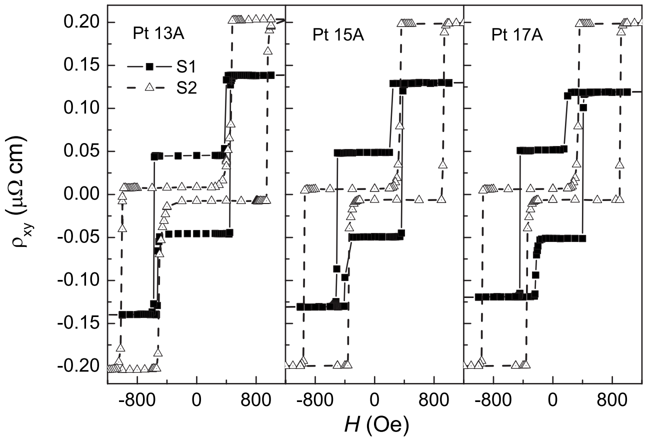

FIG. 1. Dependence of extraordinary Hall resistivity ρ_{xy} on perpendicularly applied magnetic field H for three Pt layer thickness t_{Pt} for sample series of S1 and S2.

II. EXPERIMENTS

Two series of samples are chosen to study the scaling law for the thickness and temperature dependence of EHE. The stacking sequences of samples S1 and S2 are

$$\text{S1:}100\text{Pt}/[t_{\text{Pt}}\text{Pt}/6\text{Co}]_5/8\text{Ru}/[4\text{Co}/t_{\text{Pt}}\text{Pt}]_5/50\text{Pt},$$

$$\text{S2:}100\text{Pt}/[t_{\text{Pt}}\text{Pt}/6\text{Co}]_5/8\text{Ru}/[6\text{Co}/t_{\text{Pt}}\text{Pt}]_5/50\text{Pt},$$

where thickness unit is angstrom, each ML consists of five Pt/Co double layers, and the Pt layer thickness t_{Pt} in Pt/Co MLs will be varying from 0 to 30 Å. The samples were prepared by dc and rf magnetron sputtering on Si/SiO_2 wafers with a base pressure of better than 7.5×10^{-9} Torr. The deposition rate of Pt, Co, and Ru is 1.5, 0.7, and 0.6 Å/s, respectively. Smooth interfaces for Co/Ru and Co/Pt layers have been shown in our previous work identified by cross-sectional high-resolution transmission electron microscopy.[17,18]

For the transport measurement, standard photolithography and ion-beam etching were used to pattern the samples into Hall bars with 40 μm in width and a 200 μm separation between the current leads and a 100 μm separation between the V_{xx} voltage leads, transport properties were measured with Quantum Design physical property measurement system (PPMS) by using the standard four-probe technique. The Hall hysteresis loops were measured with temperature varying from 300 to 4.2 K.

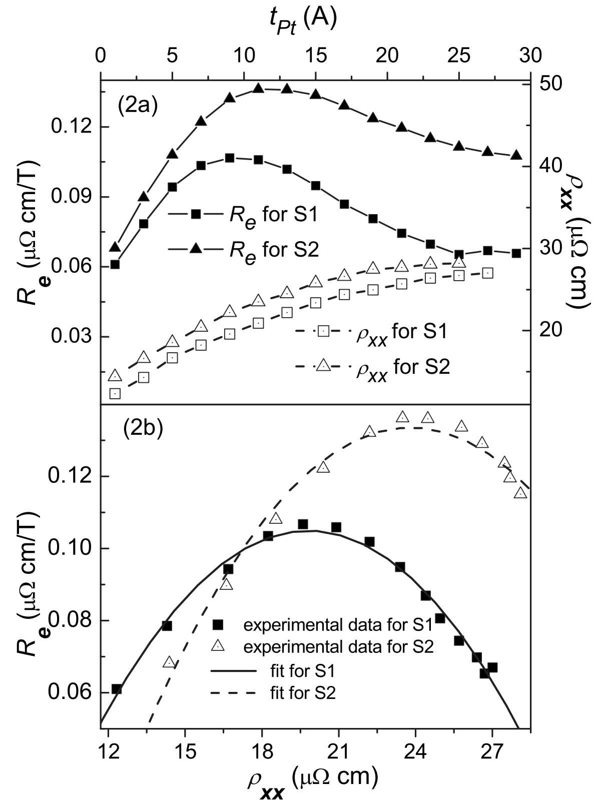

FIG. 2. (a) Hall coefficient R_e and saturated longitudinal resistivity ρ_{xx} as a function of Pt layer thickness t_{Pt} for samples S1 and S2. (b) R_e vs ρ_{xx} for samples S1 and S2, where the lines are fits to Eq. (2).

III. RESULTS AND DISCUSSIONS

We first consider the scaling relation between the Hall coefficient and resistivity for S1 and S2 series of samples with different Pt layer thickness at room temperature (RT). Figure 1 shows the Hall resistivity as a function of the perpendicularly applied magnetic field for three selected thicknesses. The perfect stepwise Hall signals indicate that the ordinary Hall signal which is proportional to the magnetic field can be completely discarded. These three steps corre-

TABLE I. Transport properties coefficients and the fitted constants of our samples with a Ru spacer and the previous results (Ref. 6) of Co/Pt superlattices without the Ru layer.

Samples	Parameters	ρ_{xx} ($\mu\Omega$ cm)	a (T^{-1})	b ($\mu\Omega$ cm T)$^{-1}$	$\left\lvert\frac{a\rho_{xx}}{b\rho_{xx}^2}\right\rvert$
S1 series	4 Å Co, 0–30 Å Pt	12–27	$+3.21\times10^{-2}$	-8.095×10^{-4}	>1
S2 series	6 Å Co, 0–30 Å Pt	14–28	$+3.73\times10^{-2}$	-7.841×10^{-4}	>1
S3	4.2–77 K	24–29	-6.93×10^{-3}	$+2.40\times10^{-4}$	>1
S3	77–300 K	29–38	-6.93×10^{-3}	$+2.40\times10^{-4}$	<1
Co/Pt (Ref. 6)	2–15 Å Co, 9–20 Å Pt	5–33	-10^{-3}–$+10^{-5}$	$+1-3\times10^{-5}$	<1

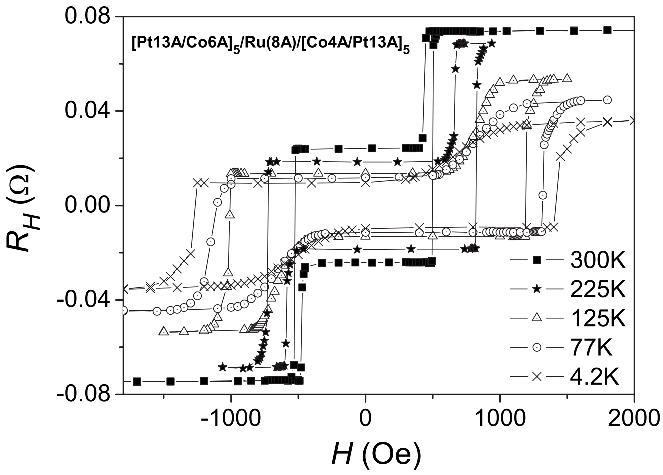

FIG. 3. Hall hysteresis loops at several different temperatures.

spond to three magnetization states. (1) At small magnetic fields, the two MLs are antiparallel and the Hall resistivity is small since the Hall voltage from the antiparallel aligned Co/Pt MLs nearly cancels; for the symmetric sample S2, the cancellation is nearly complete. (2) For the field larger than the AF coupling field, the magnetization of the two Co/Pt MLs become parallel and the Hall signal saturates.

In Fig. 2(a), we show the Hall coefficient R_e and the longitudinal resistivity ρ_{xx} for different Pt thickness. Both R_e and ρ_{xx} were taken at a large magnetic field where the magnetization and the Hall signal are saturated, i.e., $R_e=\rho_{xy}/M_s$. Note that the magnetization of the MLs comes from Co layers since Pt layers have very small magnetic moments. M_s at RT is fixed at 1100 $\mathrm{emu/cm^3}$ and 1200 $\mathrm{emu/cm^3}$ for samples S1 and S2, respectively, independent of the Pt thickness. While ρ_{xx} monotonically increases with the thickness of Pt layers, R_e reaches maximum values at $t_{\mathrm{Pt}}=9$ and 11 Å for S1 and S2, respectively. In a conventional transition-metal MLs such as Co/Cu, the increase in the nonmagnetic layer thickness always reduces R_e since the nonmagnetic layer does not contribute to R_e. For Co/Pt layers, the interface dominates the EHE. The strong hybridization between Pt 5d and Co 3d at the Co/Pt interface leads to a very large spin-orbit coupling which results in a large interface perpendicular anisotropy. This same mechanism also explains the giant EHE in Co/Pt MLs. The observed maximum R_e at $t_{\mathrm{Pt}}=9-11$ Å indicates that the spin-orbit coupling needs 3–4 Pt atomic layers to reach its maximum strength.

In Fig. 2(b), we show R_e as a function of the resistivity when t_{Pt} is varied from 0 to 3 nm for both series S1 and S2. The measured transport data along with the fitting parameters of a and b in Eq. (2) are listed in Table I. We have also included the data (last row in Table I) taken from Ref. 6 for Co/Pt MLs without the Ru spacer. Clearly both linear and quadratic terms are important in order to fit the experimental data. It is noted that the EHE is much larger in our samples than in pure Co/Pt MLs: the so-called skew scattering coefficient a is about 30 times larger and the anomalous contribution coefficient b could be as much as 80 times larger. The Hall angle θ, which is defined as $\tan\theta=\rho_{xy}/\rho_{xx}$, is about 6°, is also orders of magnitude larger than a fraction of degree found in pure Co/Pt MLs.[6]

Next, we focus on the scaling law by varying the temperature. We choose one sample from S1 series to present our data, i.e., we call sample S3 which is composed of Pt(100)/[Pt(13)/Co(6)]$_5$/Ru(8)/[Co(4)/Pt(13)]$_5$/Pt(50) (Å). The other samples in S1 and S2 displayed the similar behavior. The longitudinal and Hall resistance were determined at a saturated magnetic field at each temperature. In Fig. 3, we show the Hall hysteresis loops for five different temperatures. To determine the Hall coefficient from the measured Hall resistivity, one also needs to find the temperature dependence of the saturation magnetization. We used vibrating sample magnetometer to measure both the saturation magnetization M_s and the coercivity H_C for the unpatterned

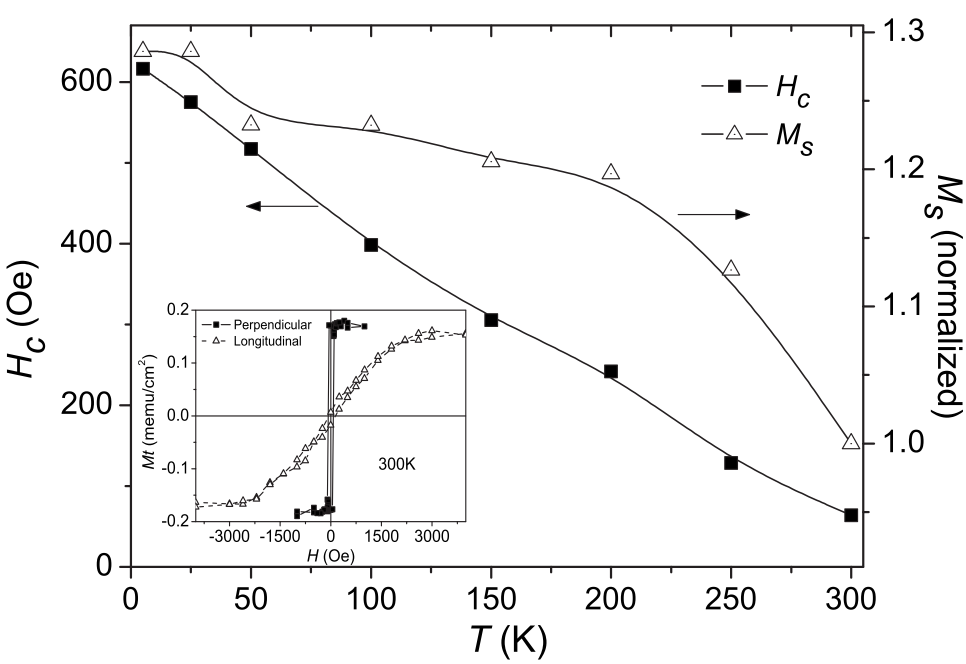

FIG. 4. Coercivity H_C and saturated magnetization M_s (normalized to that at room temperature) vs temperature T. The inset shows the perpendicular and longitudinal hysteresis loops at room temperature.

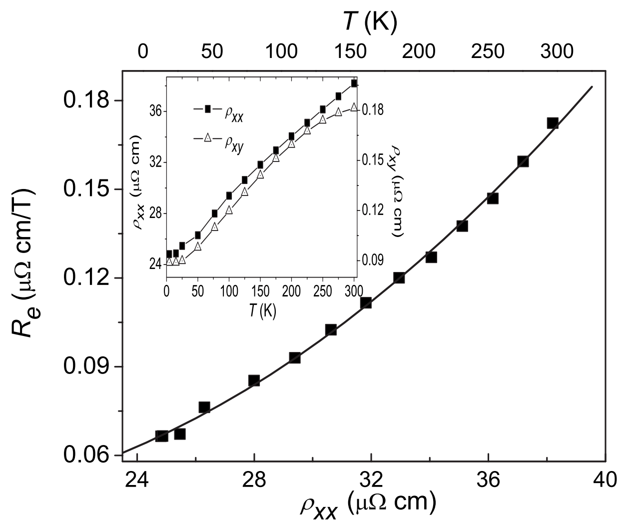

FIG. 5. Extraordinary Hall coefficient $R_e(T)$ vs the saturated longitudinal resistivity $\rho_{xx}(T)$. The solid line is the fit of Eq. (2). The inset is the temperature dependence of longitudinal and extraordinary resistivity where the lines are guided for eyes.

Pt(100)/[Pt(13)/Co(6)]$_5$/Pt(50)(Å) MLs and the result is shown in Fig. 4. Both the saturation magnetization M_s and the coercivity H_C increase when the temperature decreases, as expected. H_C increases tenfold from 64 Oe to 616 Oe, whereas saturation field H_s for sample S3 increases about three times from 548 Oe to 1800 Oe.

In Fig. 5, we show the dependence of $R_e(T)$ on $\rho_{xx}(T)$ along with the fitted curve; in the inset, we plot the temperature dependence of longitudinal and Hall resistivity. From the fitting, we find that the skew scattering is more important than the anomalous contribution when $T<77$ K. We note that the coefficients a and b derived from this temperature-dependent measurement are very different from those derived from the thickness-dependent measurement, see Table I. This certainly raises the question of the meaning of these two terms in Eq. (2). The conventional interpretation of skew scattering for the first term and of anomalous velocity (or side jump) for the second term should be either abandoned or modified.

IV. CONCLUSIONS

We have presented the EHE studies for the Ru-mediated antiferromagnetically coupled Co/Pt MLs. It is found that the EHE is much larger than that without the Ru spacer. This EHE enhancement is contributed to the Co/Ru interface scattering. Future work is needed to investigate why the interface scattering can induce such large EHE effects.

We have also shown that the conventional scaling to represent two sources of EHE can be well fitted in terms of the variation in the layer thickness and the temperature. However, the vastly different fitting coefficients for the two different ways of varying resistivity raise a serious question about the physical meaning of conventional scaling analysis. In earlier studies of EHE in magnetic multilayers and magnetic granular films, it has been known that the scaling relation is not valid.[19,20] The origin of the deviation from simple scaling relation is due to different spin-dependent scattering in the layers (or granules) and at the interfaces. Since the relative contributions from the different regions to the resistivity and to the Hall conductivities are not the same, one could arrive at different scaling relations, dependent on the ratio of the spin-dependent scattering at the interface and in the bulk, as well as the size of the granules or the thickness of the layers.[9]

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