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Unusual Anomalous Hall Effect in a Co_2MnSi/MnGa/Pt Trilayer

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An ultra-thin Co_2MnSi(0.5 nm)/MnGa(1.5 nm) bilayer capped with Pt (5 nm) has been successfully grown by molecular-beam epitaxy. It is a potential candidate of synthetic antiferromagnets due to antiferromagnetic coupling between Co_2MnSi and MnGa, which is a promising skyrmion-racetrack-memory medium without skyrmion Hall effect after capping with a Pt layer. Unusual humps in transverse Hall resistance loops are clearly observed in the temperature range from 260 to 400 K. This anomaly is generally attributed to topological Hall effect, but other than that, we prove that non-uniform rotation of magnetic moments in the bilayer with magnetic field sweeping is also a possible mechanism contributed to the unusual hump.

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In the past decade, magnetic skyrmions have been a focus of intensive research for their abundant physical properties[1−5] and applicable advantages, such as small size, topological stability and low driven current density.[6−10] During electrical transmission, similar to Hall effect of traditional charges in magnetic field, topological charges are collected at the side of the sample due to the Magnus force, and it is expressed as skyrmion Hall effect (SkHE).[11−14] It largely decreases the transmission distance of magnetic skyrmions and severely limits the applications on small size devices. However, it was reported that SkHE could be absent in the synthetic antiferromagnet (SAFM).[15−17] The studies of magnetic skyrmions in SAFM will provide the foundation for practical applications of magnetic skyrmions on storage technologies.

When conduction electrons across a topological non-trivial spin texture, such as magnetic skyrmions, an emergent fictitious magnetic field produces an excess part of Hall resistance (or Hall conductance), which is termed as topological Hall effect (THE).[18,19] In addition to the direct image methods to detect magnetic skyrmions,[20−23] THE measurement has been widely used to characterize magnetic skyrmions because of its simplicity and convenience. It is widely known that THE has been observed in some chiral bulk materials or thin films without central inversion symmetry with magnetic skyrmions appearing at low temperature.[24−28] Recently, THE signal has also been detected in magnetic multilayer with interfacial Dzyaloshinskii–Moriya interaction (DMI),[29,30] in which magnetic skyrmions exist in a large range of temperature.[23,31−33]

In this letter, we propose an SAFM based on a thin antiferromagnetically coupled Co_2MnSi/MnGa bilayer[34−36] with a Pt capping layer. The interfacial DMI-induced magnetic skyrmion state without SkHE is expected in this structure, which makes it a potential skyrmion-racetrack-memory medium without SkHE. Magnetic and transport properties of this composite are investigated in detail.

The whole structure of our sample is shown in Fig. 1(a), in which the Co_2MnSi(0.5 nm)/MnGa(1.5 nm) bilayer was grown on a GaAs (001) substrate at 250℃ by molecular-beam epitaxy (MBE), while a 5 nm Pt capping layer was deposited using e-beam evaporation at room temperature in the same MBE growth chamber. The surface crystalline structure was monitored *in-situ* by reflection high-energy electron diffraction (RHEED). The observed streaky RHEED patterns during the growth of Co_2MnSi and MnGa indicate the single crystal structure of the bilayer. The cross-sectional high-resolution transmission electron microscope (HRTEM) images are shown in Fig. 1(b). The observed clear crystal structures and interfaces further indicate high-quality growth of Co_2MnSi/MnGa/Pt trilayer. The magnetization measurements were carried out using a superconducting quantum interference device (SQUID) magnetometer. The sample was then patterned into Hall bars with 10 μm width and 120 μm length by ultraviolet lithography and dry etch-

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ing, and the gold contact electrodes were deposited by thermal evaporation, as shown in Fig. 1(c). The magnetic transport behavior was measured by a physical property measurement system (PPMS).

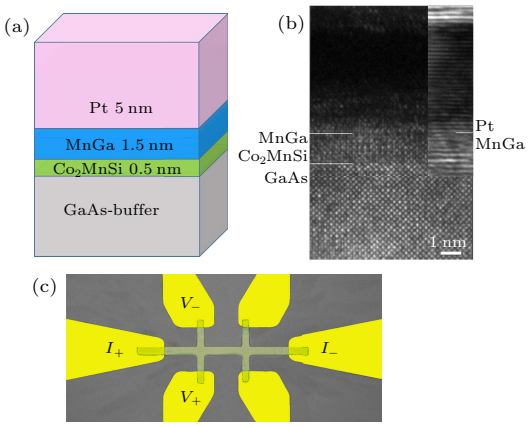

Fig. 1. (a) Schematic diagram of the sample. (b) The cross-sectional HRTEM images of the sample. Inset: the cross-sectional HRTEM image of clear Pt/MnGa interface in another region with the same scale of Fig. 1(b). (c) Microscope photograph of a Hall bar device (120 μm ×10 μm).

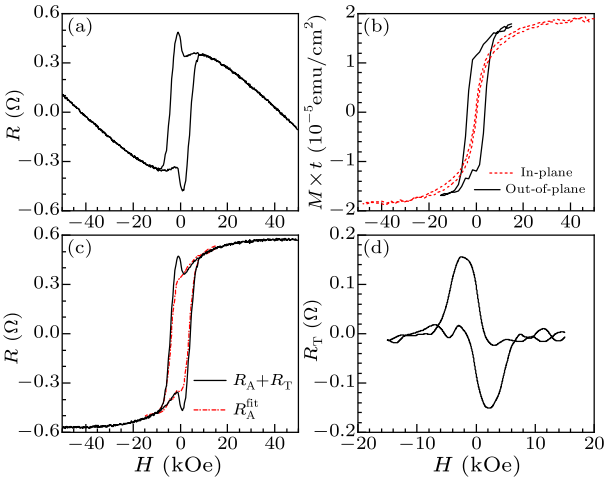

Fig. 2. Magnetic field dependence of (a) total Hall signal, (b) out-of-plane and in-plane magnetization, (c) Hall signal after subtracting the OHE part (black solid line) and the fitted AHE signal (red dotted line) and (d) the calculated topological Hall signal at room temperature.

At room temperature, the total Hall signal of the trilayer is shown in Fig. 2(a). Different from the square loop of typical magnetic metal, two extra peaks are clearly observed, in addition to the contribution of the ordinary Hall effect (OHE) and anomalous Hall effect (AHE). The out-of-plane and in-plane magnetization curves are shown in Fig. 2(b). Non-steep flips indicate that the magnetic moments are not completely vertical and there is an in-plane component in the sample. After the OHE signal is subtracted from the total Hall signal, the rest Hall signal is shown in Fig. 2(c). Due to the competition between magnetic dipolar interaction and perpendicular magnetic anisotropy, and the DMI induced by the heavy metal layer of Pt, it is assumed that the unusual AHE comes from magnetic skyrmions. The total Hall resistance R consists of three parts as reported by several groups,[26,37,38] and can be expressed as

$$R = R_{\mathrm{O}} + R_{\mathrm{A}} + R_{\mathrm{T}}, \tag{1}$$

where R_{O}, R_{A} and R_{T} denote resistance contributions from OHE, AHE and THE, respectively. Therefore, R_{T} could be extracted by subtracting the contributions of the OHE and AHE from the total Hall signal. As shown in Fig. 2(c), it is assumed that the fitted AHE signal is scaled from the out-of-plane magnetization hysteresis, which is discussed later under the condition that the two magnetic moments of the bilayer rotate uniformly with the magnetic field. The calculated curve of R_{T} is given in Fig. 2(d).

However, debates about the origin of the unusual AHE also exist, e.g., Kan *et al.*[39] and Gerber[40] proposed a mechanism that the anomaly in AHE is originated from inhomogeneous magnetoelectric properties in materials such as $SrRuO_3$ and $[Co_{0.2}/Pd_{0.9}]_6/[Co_{0.4}/Pd_{0.9}]_6$, which means that the anomaly may be originated from AHE itself. On the other hand, Meng *et al.*[32] demonstrated that magnetic skyrmions exist in $SrIrO_3/SrRuO_3$ bilayer by magnetic force microscopy recently. Meng *et al.*[33] thought it is an interface-driven effect independent of THE in Mn_xGa/Pt bilayers. For this Co_2MnSi/MnGa/Pt trilayer with antiferromagnetic coupling, we propose a simple model to describe the relationship between net magnetization and AHE signal. For simplicity, the resistances of the two ferromagnetic layers are assumed to be comparable. The out-of-plane magnetization and anomalous Hall voltage of the two ferromagnetic layers are defined as $M_{i\perp}$ and V_i, respectively. The relationship between the magnetic moment of each ferromagnetic layer with the magnetic field is defined as

$$M_{i\perp} = M_{i,\mathrm{s}}(T) f_i(H), \tag{2}$$

where $M_{i,\mathrm{s}}$ is the saturation magnetization and $f_i(H)$ is a monotonic function of magnetic field. The total out-of-plane magnetization of the bilayer can be expressed as

$$M_{\mathrm{T}\perp} = \frac{M_{1\perp}t_1 \pm M_{2\perp}t_2}{t_1 + t_2}, \tag{3}$$

where t_i represents the thickness of each film. The total anomalous Hall voltage of the bilayer can be written as

$$\begin{aligned} V_{\mathrm{T}} &= \frac{V_1 + V_2}{2} = \frac{1}{2}\left(\frac{\mu_0 I_1 R_1 M_{1\perp}}{2t_1} \pm \frac{\mu_0 I_2 R_2 M_{2\perp}}{2t_2}\right) \\ &= \frac{\mu_0 I}{4}\left(\frac{R_1 M_{1\perp}}{t_1} \pm \frac{R_2 M_{2\perp}}{t_2}\right), \end{aligned} \tag{4}$$

where μ_0 is the permeability of vacuum, I_i and R_i are the respective longitudinal current and AHE coefficient of each layer, and I is the longitudinal current which is equal to both I_1 and I_2. If the two magnetic moments rotate consistently with the magnetic field, then

$$f_1(H) = kf_2(H), \tag{5}$$

$$M_{T\perp} = \frac{M_{1,s}kt_1 \pm M_{2,s}t_2}{t_1 + t_2} f_2(H), \tag{6}$$

$$V_T = \frac{\mu_0 I}{4}\left(\frac{M_{1,s}kR_1}{t_1} \pm \frac{M_{2,s}R_2}{t_2}\right) f_2(H). \tag{7}$$

Therefore, when the two magnetic moments of the bilayer rotate uniformly with the magnetic field, V_T and $M_{T\perp}$ have the same tendency as the magnetic field changes, and the unusual AHE hump will not appear in a small magnetic field range for the bilayer with strong magnetic coupling and good in-plane uniformity. In contrast, if the two magnetic moments rotate non-uniformly corresponding to the case of weak magnetic coupling, then

$$f_1(H) \neq kf_2(H), \tag{8}$$

and when the anomalous Hall coefficients of the two ferromagnetic layers are opposite, the anomalous Hall curve could exhibit the unusual hump feature similar to THE, as reported by Kan *et al.*[39] and Gerber.[40]

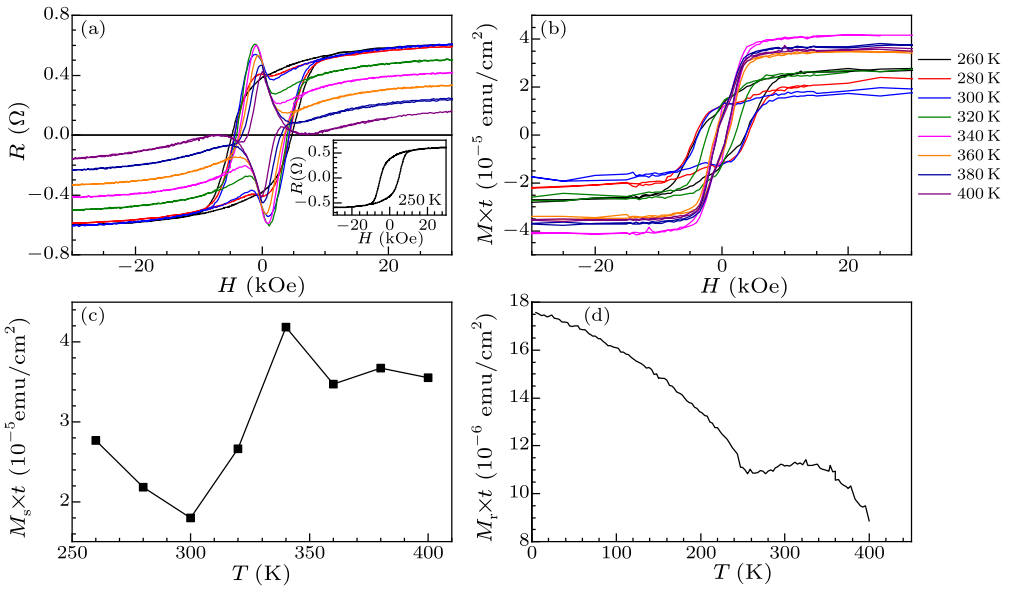

Fig. 3. (a) Hall signal after subtracting the OHE part and (b) out-of-plane magnetization dependence on magnetic field at different temperatures. Inset: magnetic field dependence of Hall signal after subtracting the OHE part at 250 K. (c) Out-of-plane saturation magnetization and (d) out-of-plane residual magnetization dependence on temperature.

The possibility that the observed unusual AHE originated from the above reasons in this sample is further explored. In the temperature range from 260 to 400 K, the Hall curves (after subtracting the OHE part) and the magnetic hysteresis loops are shown in Figs. 3(a) and 3(b), respectively. Noting that at 400 K, near the saturated magnetic field, symmetric two points of zero resistance appear in the Hall curve. It can be inferred that the anomalous Hall coefficients of the two ferromagnetic layers must be opposite at this temperature. It is reported that the anomalous Hall coefficient of a material is related to the material composition and temperature,[39,40] and the anomalous Hall coefficient of Co_2MnSi is easily affected due to interfacial interdiffusion with the GaAs substrate. At the same time, in the temperature range from 260 to 400 K, as the temperature increases, the saturation magnetization varies non-monotonically, and the value is always larger than the low-temperature one at temperature above 340 K, as shown in Fig. 3(c). This indicates that with temperature increasing, the amount of de-coupled magnetic moments is increased, and the antiferromagnetic coupling of the two ferromagnetic layers is weakened. However, at temperature below 250 K, this unusual AHE disappears, as shown in the inset of Fig. 3(a). It is caused by the enhanced antiferromagnetic coupling of the two ferromagnetic layers, which makes the two magnetic moments rotate coherently with the magnetic field. The temperature dependence of the out-of-plane residual magnetization is plotted in Fig. 3(d). With temperature increasing, the net residual magnetization gradually decreases first, starting from a plateau stage at 250 K, then appears to be a small increase, after that, gradually decreases above 340 K. It proves that the antiferromagnetic coupling between the two ferromagnetic layers is grad-

ually destroyed at temperature above 250 K. When the temperature is over 340 K, the antiferromagnetic coupling between the two ferromagnetic layers is very weak, and the magnetic moments of the two ferromagnetic layers rotate almost completely independently, and obvious unusual AHE humps were observed at this temperature range.

In summary, a Co_2MnSi/MnGa/Pt SAFM trilayer has been successfully grown by MBE. Unusual AHE humps are clearly observed in the temperature range from 260 to 400 K, which is a possible indication of the occurrence of magnetic skyrmions in this composite. Besides the THE induced by magnetic skyrmions, our results strongly reveal that non-uniform rotation of magnetic moments in the bilayer with magnetic field sweeping is also a possible mechanism contributed to the unusual AHE. Further studies by powerful visualization tools, such as Lorentz transmission electron microscope at different temperatures, are needed to clarify the mechanisms of our results.

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