Anomalous Hall Effect in MnAl/W bilayers: Modification from strong spin Hall effect of W

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Abstract: We report systematic measurements of anomalous Hall effect (AHE) in MnAl/W bilayers modified by strong spin Hall effect (SHE) of the heavy metals, in which a single $L1_0$ -MnAl epitaxial layer reveals obvious orbital two-channel Kondo (2CK) effect. The results are compared with the AHE in MnAl/Cu with weak spin orbit coupling. As increasing the thickness of W, the strong SHE has gradually suppressed the orbital 2CK effect and modified the AHE of MnAl. A scaling involving multiple competing scattering mechanisms has been used to distinguish different contributions to the modified AHE. The direct observation of spin-orbit torque induced magnetization switching confirms that the result is a combination of the AHE of MnAl and SHE of W.

Keywords: Spin transport through interfaces; Spin-orbit coupling; Magnetoelectronics

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1. Introduction

The anomalous Hall effect (AHE) is the most prominent phenomenon that exists in ferromagnetic materials (FM), which originates from the interplay between spin orbit coupling (SOC) and magnetism [1]. Electrons moving through a FM will acquire a transverse velocity with opposite directions for different spin orientations due to SOC, since the charge currents have usually a net polarization, this spin-dependent transverse velocity will result in a net transverse anomalous Hall voltage [2]. Recent investigations have both theoretically and experimentally explored the possible mechanisms of AHE through giving a unified scaling describing the AHE resistivity ρ_{AH} in terms of the longitudinal resistivity ρ_{xx} . Karplus and Luttinger have proposed that the intrinsic AHE arises from the transverse velocity of Bloch electrons induced by SOC together with interband mixing, giving $\rho_{\text{AH}} \sim \rho_{\text{xx}}^2$ [3-8]. On the other hand, the extrinsic mechanisms including skew scattering and side jump come from the asymmetrical scattering of conduction electrons due to SOC, giving $\rho_{\text{AH}} \sim \rho_{\text{xx}}$ and $\rho_{\text{AH}} \sim \rho_{\text{xx}}^2$, respectively [9-11]. Notably, in contrast to the conventional picture that ρ_{AH} scales with the total resistivity irrespective of its sources [12], recent experimental studies have revealed that both ρ_{AH} and the scaling relation are qualitatively different for various types of electron scattering. Working on epitaxial GaAs/Fe films, Tian *et al* have limited the scattering of electrons to two sources, one by interface roughness and another by phonons, with independent control on their strengths through the film thickness and sample temperature [13]. They developed the experimental strategy neglecting the contribution of phonon skew scattering, giving the scaling $\rho_{\text{AH}} = a_0 \rho_{\text{xx}0} + b \rho_{\text{xx}}^2 = k_0 \rho_{\text{xx}0} + \beta \rho_{\text{xx}0}^2 + b \rho_{\text{xx}}^2$, where $\rho_{\text{xx}0}$ is the residual resistivity induced by impurity scattering. However, most recently, Hou *et al* have derived a general scaling relation for the AHE in FM involving multiple competing scattering mechanisms, described by a quadratic hypersurface in the space spanned by the partial resistivities, giving [14]:

$$\rho_{\text{AH}} = \alpha \rho_{\text{xx}0} + \beta_0 \rho_{\text{xx}0}^2 + \gamma \rho_{\text{xx}0} \rho_{\text{xxT}} + \beta_1 \rho_{\text{xxT}}^2 \quad (1)$$

where $\rho_{\text{xx}0}$ is the residual resistivity induced by impurity scattering, $\rho_{\text{xxT}} = \rho_{\text{xx}} - \rho_{\text{xx}0}$ is

due to dynamic disorders (mainly phonons at higher temperatures), α is the skew scattering coefficient, the coefficients β_0 , β_1 and γ contain intrinsic Berry curvature and side-jump contributions. Spin Hall effect (SHE) that converts charge currents into spin currents in a heavy metal (HM) with strong SOC has attracted much interest due to its practical use in technological applications [15-22]. In these hybrid structures, spin and charge transport phenomena are interconnected, and HM may serve as both spin current generator and detector. The spin currents that diffuse into the FM will modify the spin dependent transport properties such as AHE [23]. On the other hand, the spin currents will also exert torque on the magnetization, which is similar to spin transfer torque [24-31]. Considering the essence of AHE, the modification from SHE can also be explored through clarifying $\rho_{\text{AH}} \sim \rho_{\text{xx}}$ relations [23].

Another spin-dependent transport behavior that can dramatically influence the AHE is the orbital two-channel Kondo (2CK) effect [32]. When a pseudo-spin 1/2 of structural two-level system strongly couples to two spin channels of conduction electrons, the orbital 2CK effect will become evident with displaying exotic non-Fermi liquid (NFL) behavior [33]. The 2CK effect has a unique temperature (T) dependence in resistivity with three different T ranges: a low T upturn $\Delta\rho_{\text{xx}}$, which scales with $\ln T$ beyond the Kondo temperature T_K , followed by NFL behavior $\Delta\rho_{\text{xx}} \sim T^{1/2}$ for $T_D < T < T_K$ as the consequence of two conduction electron spins screening, then at extreme low temperature a deviation from $T^{1/2}$ dependence has happened [32-34]. The most remarkable characteristic in the orbital 2CK effect is the NFL behavior $\Delta\rho_{\text{xx}} \sim T^{1/2}$, which is much different from the $\Delta\rho_{\text{xx}} \sim T^2$ scaling of Fermi-liquid behavior in fully screened Kondo effect. Recently, Zhu *et al.* have reported that the AHE in perpendicularly magnetized MnAl epitaxial films with a variable orbital 2CK effect [32]. The AHE is observed to excellently scale with $\rho_{\text{AH}}/f = a_0\rho_{\text{xx}0} + b\rho_{\text{xx}}^2$ at high temperatures. However, a significant deviation happens at low temperatures where the orbital 2CK effect becomes important, which agrees with the orbital 2CK effect in the breakdown temperatures and deviation magnitudes.

In this context, as an attempt to offer a step towards exploring these rich and underlying physics, we have systematically investigated the AHE in MnAl/W films,

in which a single $L1_0$ -MnAl epitaxial layer reveals obvious orbital 2CK effect. The strong SHE of W has suppressed the orbital 2CK effect and modified the AHE of MnAl. The results are compared with those in MnAl/Cu(6nm) bilayers, in which Cu has very weak SOC. It is found that the spin-dependent transport properties in MnAl/W(t) (t is in nanometre) are much different from that in the MnAl single layer and the MnAl/Cu films. Using the scaling developed by Hou *et al*, different contributions to the modified AHE in MnAl, MnAl/Cu and MnAl/W can be distinguished [14]. The scaling analysis reveals that the most evident modification happened in the coefficients γ and β_1 . The modified AHE is a combination of the AHE in MnAl and SHE in W, which is proved by the measurement of SOT.

2. Experimental details

A 4-nm-thick $L1_0$ -MnAl single-crystalline film was grown on a semi-insulating GaAs (001) substrate by molecular-beam epitaxy at substrate temperature $T_S=473$ K. Here the Mn/Al atoms ratio is 1. Then, Cu, and W films with different thickness $t=2, 4, 6$ nm were deposited on it by dc magnetron sputtering immediately. Photolithography and Ar ion milling were used to pattern Hall bars and a lift-off process was used to form the contact electrodes. The size of all the Hall bars is $10\ \mu\text{m}\times 80\ \mu\text{m}$. The transport measurements were carried out in a physical property measurement system (PPMS). We have also measured the temperature dependent resistivities of single Cu and W films. Then, assuming that each film in the MnAl/Cu and MnAl/W bilayers acts as a parallel resistance path, both the AHE resistivity ρ_{AH} and the longitudinal resistivity ρ_{xx} in this manuscript have been expressed as those of the MnAl layer.

3. Results and discussion

The normalized out-of-plane hysteresis loops of MnAl film is shown in Figure 1(a). The perpendicular M-H curve shows a square-like shape revealing its giant perpendicular magnetic anisotropy (PMA). Fig. 1 (b) plot the T dependence of the resistivity variation at $H=0$ Oe and $H=80000$ Oe for the $L1_0$ -MnAl film, the ρ_{xx} under these two magnetic field all show an increase arising from the orbital 2CK effect. Fig. 1 (c) and (d) have shown distinct characteristic, which is a typical transport behavior of orbital 2CK effect. The longitudinal resistivity ρ_{xx} firstly varies linearly with $\ln T$

as increasing T from 300 K. Then, ρ_{xx} deviates from the $\ln T$ dependence and turns to a $T^{1/2}$ dependence when T is below $T_K=105$ K. The large T_K of the $L1_0$ -MnAl film suggests a strong coupling between a pseudo-spin 1/2 of structural two-level system and the two spin channels of conduction electrons. The $T^{1/2}$ -dependent resistivity is a distinguishing feature of the NFL behavior for the 2CK effect. As further decreasing temperature, ρ_{xx} begins to increase faster than $T^{1/2}$ below a characteristic temperature $T_D=40$ K. On the other hand, magnetic fields H should not have any observable influence on the orbital 2CK effect via changing the population balance of the two spin channels of the conduction electrons. The H -independent resistivity upturn as shown in Fig. 1(a) scaling with $\ln T$ and $T^{1/2}$ in the two T regimes, and the deviation from the NFL behavior at the lowest temperatures are consistent with the transport properties in two-level systems [32, 33].

After depositing a 6-nm-thick Cu film, the orbital 2CK effect has not been changed evidently, as shown in Fig. 2(a). Notably, comparing the T dependent of ρ_{xx} in MnAl and MnAl/Cu, evident suppression has been found in MnAl/W(4nm) and MnAl/W(6nm) as shown in Fig. 2(c) and (d). At a characteristic temperature ($T_M=90$ K), there is a resistivity minimum of ρ_{xx} for the MnAl/W(4nm) bilayer. In the high T range ($T>T_M$), ρ_{xx} increases linearly with T due to the increasing phonon scattering, and T_K decreases to 50 K. The T_K and T_D of all the films have been evaluated from Fig. 1 and 3. The suppression gradually increased as increasing the thickness of W with further decreasing T_K and T_D as summarized in Table I. Notably, as discussed by Zhu *et al*, the ferromagnetic exchange splitting of the d -band will lead to an imbalance in the channel population and quench the NFL behavior, which is characterized by an enhanced effective breakdown temperature of the 2CK effect [33]. The channel asymmetry should lead to different tunnelling rates of the two-level system for two spin channels and thus weaken the NFL behaviors in comparison with its nonmagnetic counterpart ($\Delta N=N_{\uparrow}-N_{\downarrow}=0$), where $N_{\uparrow}$ and $N_{\downarrow}$ are the density of states for majority and minority spin channels in the conduction band. Based on the Stoner model for itinerant ferromagnetism, the saturation magnetization M_s can be used as an index for the degree of spin population imbalance of the conduction band.

The small M_S of the MnAl film studied here indicates a very low degree of spin population imbalance with the loss of the chemical ordering. This could be the reason why the ferromagnetic exchange splitting does not quench the 2CK physics [31]. Considering the enhanced channel asymmetry will weaken the NFL behavior, we suppose that the orbital 2CK effect will be suppressed if the pure spin current generated by the metals with strong SOC, such as W, diffuses into the FM. The spin polarization at the Fermi surface will be modified and the enhanced ΔN will quench the orbital 2CK effect.

Fig. 4(a) shows the T profiles of ρ_{AH} for all the five samples, which all decrease as cooling down. So far, there have been few reports on a similar anomaly in the T dependence of ρ_{AH} [35]. We infer that the strong orbital 2CK effect in $L1_0$ -MnAl could be the reason for such a complex T dependence of ρ_{AH} . We plot ρ_{AH} as a function of ρ_{xx} for all the samples to compare the difference of scaling curves in Fig. 4 (b). It is found that the function of $\rho_{AH}(\rho_{xx})$ in MnAl is much different with MnAl/W. Moreover, varying the thickness of W also changes the function of $\rho_{AH}(\rho_{xx})$. Considering that the conductivity of ultrathin MnAl film is small enough, we firstly use the scaling given by Tian *et al* for describing the AHE in this system [13]. In Fig. 4(c), the ρ_{AH} is plotted versus the longitudinal resistivity square ρ_{xx}^2 . However, we found that for all the films these plots have not shown linearity from high temperature to low temperature, indicating that this scaling cannot work. It is indicated that the intrinsic anomalous Hall conductivity is temperature dependent, which can be ascribed to the orbital 2CK effect.

Then, using Equation (1), we have taken experimental data of $\rho_{AH}(\rho_{xx})$ and fitted curves in MnAl, MnAl/W(4nm) and MnAl/W(6nm) as examples as shown in Fig. 5. It is found that the scaling works well for MnAl at the whole range of temperature. A deviation happened at low temperatures in MnAl/W(6nm), where the orbital 2CK effect becomes important. For MnAl/W(4nm), the scaling has been used at different range of temperature $T < 90K$ and $T > 90K$ respectively, and different coefficients have been deduced as shown in Table II. The most evident modification happened in the coefficients γ and β_1 . As discussed by Hou *et al.*, it is really hard to

separate out the intrinsic part from the side-jump one in β_1 and γ [14]. However, $(\beta_0 + \beta_1 - \gamma)$ and $(\gamma - 2\beta_1)$ are the coefficients of pure scattering effect and they have also changed sign with thick HM ($t > 4$ nm). Given that only the four parameters (and their linear combinations) can be extracted, it seems challenging to unambiguously separate out the intrinsic contribution from such experimental approach. This will surely motivate further experimental studies in near future. Considering the chemical ordering of MnAl has not been changed, the variation of extrinsic contribution should partly come from the asymmetric scattering due to the effective SOC at the interface and partly come from the modification from injected spin-polarized current.

To further verify our proposition, we have carried out the SHE induced switching of perpendicular magnetization in for MnAl/W(6nm). The ρ_{AH} was measured as a function of perpendicular magnetic field under different input currents (1, 8, 12 mA) as shown in Fig. 6. When the input current is as small as 1 mA, the coercivity of MnAl/W(6nm) is about 10000 Oe. As the current is increased to 12 mA, the coercivity dramatically decreases to 6000 Oe. On the other hand, ρ_{AH} has also decreased. We believe it is due to the increase of current-induced torque related with SHE as discussed MnGa/Ta films [23]. However, the current-induced torque has not been found in MnAl/Cu films. Thus it further confirms that the modified AHE discussed above stems from the SHE in the heavy metals, and the result is the combination of the AHE of MnAl and the SHE of the heavy metals.

4. Summary

In summary, we have systematically investigated AHE in MnAl/W bilayers modified by strong SHE of the heavy metals, in which a single $L1_0$ -MnAl epitaxial layer reveals obvious orbital 2CK effect. The results are compared with the AHE in MnAl/Cu with weak spin orbit coupling. As increasing the thickness of W, the strong SHE has gradually suppressed the orbital 2CK effect and modified the AHE of MnAl. A scaling involving multiple competing scattering mechanisms has been used to distinguish different contributions to the modified AHE. The scaling analysis reveals that the most evident modification happened in the coefficients γ and β_1 . The direct observation of SOT induced magnetization switching confirms that the result is a

combination of the AHE of MnAl and SHE of W.

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Figure Captions

Fig. 1 (a) The normalized out-of-plane hysteresis loop of MnAl film. (b) ρ_{xx} vs T at $H=0$ Oe (a) and $H=80000$ Oe for MnAl film. (c) and (d) ρ_{xx} vs T for MnAl film in different range of temperature.

Fig. 2 The temperature dependence of the longitudinal resistivity ρ_{xx} for MnAl/Cu(6nm) and MnAl/W(t) films.

Fig. 3. The temperature dependence of the longitudinal resistivity ρ_{xx} for MnAl/Cu (6nm) and MnAl/W (t). The red line is the fitted curve.

Fig. 4 (a) The temperature dependence of ρ_{AH} for the five samples. (b) ρ_{AH} as the function of ρ_{XX} for the five samples. (c) ρ_{AH} as the function of ρ_{XX}^2 for the five samples.

Fig. 5 ρ_{AH} as the function of ρ_{XX} for the MnAl, MnAl/W(4nm) and MnAl/W(6nm) films.

Fig. 6 ρ_{AH} as the function of magnetic field with the input currents of 1, 8 and 12 mA in MnAl/W(6nm) film.

TABLE I. T_D and T_K for the five samples.

	MnAl	MnAl/Cu(6nm)	MnAl/W(2nm)	MnAl/W(4nm)	MnAl/W(6nm)
T_D (K)	40	40	30	10	~
T_K (K)	105	100	80	50	10

TABLE II. The AHE scaling coefficients for the five samples.

	α	$\beta_0 (\mu\Omega^{-1}\text{cm}^{-1})$	$\gamma (\mu\Omega^{-1}\text{cm}^{-1})$	$\beta_1 (\mu\Omega^{-1}\text{cm}^{-1})$
MnAl	6.5e-3	3.1e-5	1.1e-4	-1.4e-4
MnAl/Cu(6nm)	4.2e-3	2.1e-4	3.5e-3	-2.2e-3
MnAl/W(2nm)	1.1e-2	1.7e-4	3.3e-4	-2.6e-4
MnAl/W(4nm) ($T < 90\text{K}$)	2.1e-2	5.4e-5	3.2e-4	-3.7e-3
MnAl/W(4nm) ($T > 90\text{K}$)	2.0e-2	5.1e-5	-8.9e-4	1.3e-2
MnAl/W(6nm)	5.9e-2	2.7e-5	-2.7e-4	8.6e-2