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Evolution of anomalous Hall behavior in thin Pt/Co/Pt trilayers

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ABSTRACT

In this work, through controlling spin scattering mechanisms, anomalous Hall behaviors exhibit a series of evolutions in thin Pt/Co/Pt trilayers. The shape of Hall resistivity over longitudinal resistivity (ρ_{AH}/ρ_{xx} versus ρ_{xx}) curve turns from bending to linear and then bending again in most trilayers. This kind of evolution cannot be explained by the conventional linear scaling of anomalous Hall effect. It should be ascribed to the contribution of spin-phonon skew scattering. Our research may help to understand spin scattering behavior in low-dimensional systems more deeply and build a proper synergy between theory and experiment on the research of anomalous Hall effect.

1. Introduction

Some recent hot research topics such as spin Hall effect [1], spin Seebeck effect [2], magnetic proximity effect [3,4], anomalous Nernst effect [5–7] and spin torques [8,9] have been found being closely involved with spin orbit coupling (SOC). As the earliest discovered magneto-transport phenomena, anomalous Hall effect (AHE) attracts interest once again because it is unambiguously one of the most powerful methods to explore the SOC. Also, AHE has potential application in high sensitivity Hall sensors [10–12]. In general, anomalous Hall resistivity (ρ_{AH}) is determined by the skew scattering ($\propto\rho_{xx}$) [13,14], intrinsic Berry curvature of energy bands [15] ($\propto{\rho_{xx}}^2$), and side-jump mechanism [16] ($\propto{\rho_{xx}}^2$), where ρ_{xx} is longitudinal resistivity. Then a conventional expression can be phenomenologically written as

$$\rho_{AH} = a\rho_{xx} + b\rho_{xx}^2. \tag{1}$$

If the material, for example Mn_5Ge_3 [17], has a strong temperature dependent spontaneous magnetization (M), the parameters a and b must be modified according to the temperature dependent function $f(T)$, and thus Eq. (1) was revised as

$$\rho_{AH} = af(T)\rho_{xx} + bf(T)\rho_{xx}^2. \tag{2}$$

Although there had been lots of debates on the origins of AHE in theory, explanations for experimental works were usually based on the above two equations for a long time until 2009. In this year, Tian et al. [18] pointed out that the skew scattering item should be divided into two parts according to the Matthiessen rule: one stems from impurity scattering and the other from electron–phonon scattering. The phenomenological expression should be modified by a new scaling,

$$\rho_{AH} = a'\rho_{xx0} + a''\rho_{xxT} + b\rho_{xx}^2, \tag{3}$$

where ρ_{xx0} is residual resistivity and ρ_{xxT} is resulted from thermal activity. Furthermore, some researchers tried to refine the new scaling and introduced more parameters, which weakens the creditability of the new scaling somehow [19,20].

Up to now, the validity of the new scaling rule is not fully explored, while the conventional scaling is being frequently used. The conventional scaling displays a linear behavior of Hall angle (i.e. ρ_{AH}/ρ_{xx}) versus ρ_{xx}. However, it is obvious that the new scaling exhibits a nonlinear dependence of Hall angle on ρ_{xx} (see Eq. (3)) since there is no reason to always make $a' = a''$. Thus a natural question was raised: why such a linear relationship between Hall angle and longitudinal resistivity can be used to explain previous observations if the new scaling (nonlinear) is valid?

To answer and clarify all these questions, we therewithal prepared a series of Pt/Co/Pt trilayers with an equal number of spin scattering sources, in which the competition among the three mechanisms could be changed by post-annealing temperatures (T_a).

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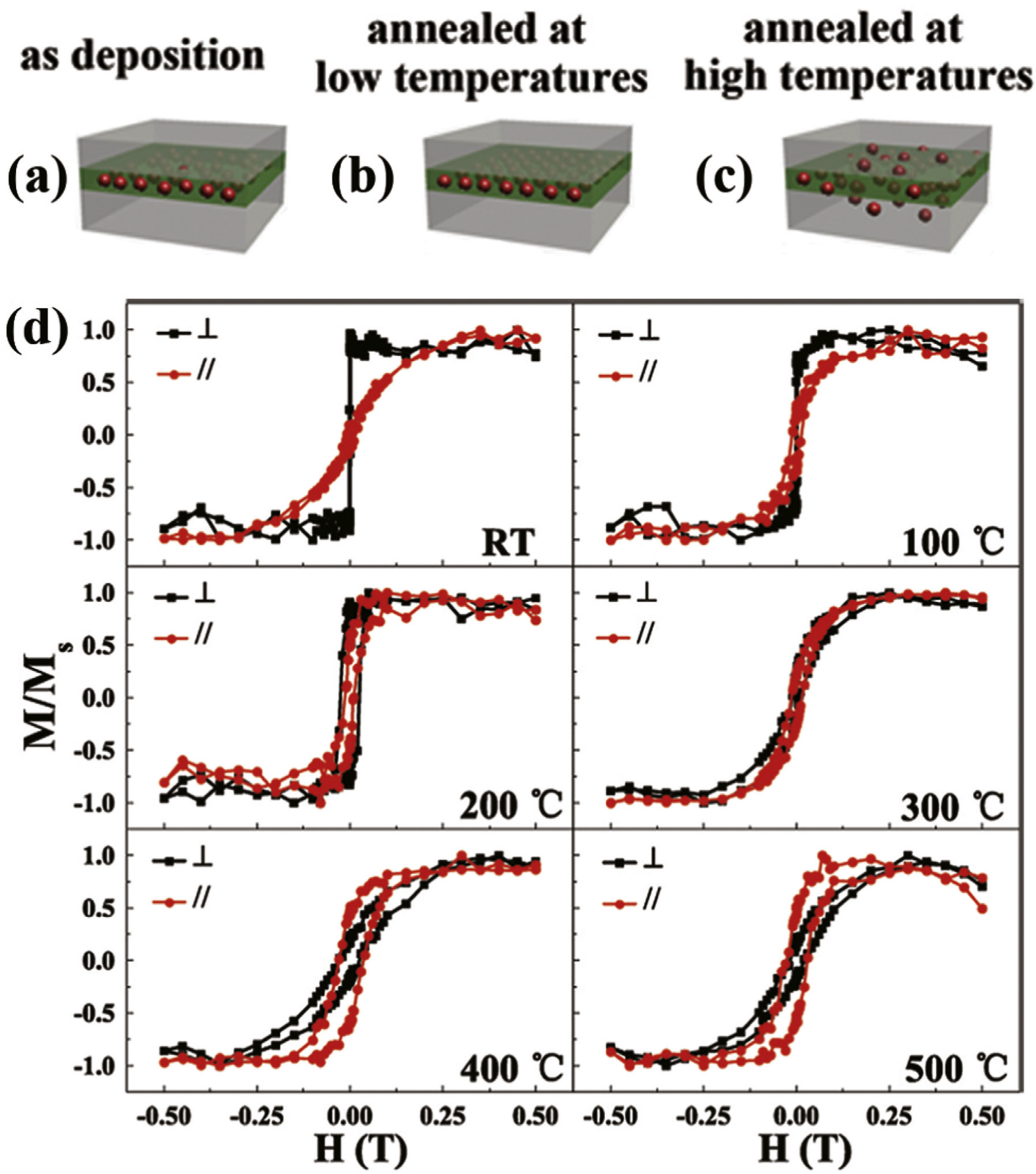

Fig. 1. Diagrammatic sketch of Co atom distribution in Pt/Co/Pt trilayers under different thermal treatments: (a) as-deposited, (b) post-annealed at low temperatures, (c) post-annealed at high temperatures, (d) hysteresis loops of Pt (2.5 nm)/Co (0.5 nm)/Pt (2.5 nm) trilayers with various annealing temperatures.

2. Experiments

Pt (t nm)/Co (0.5 nm)/Pt (5-t nm) trilayers with thickness (t) of 1, 1.75, 2.5, 3.25 and 4 nm were prepared on MgO(100) substrates by direct current sputtering under the Ar pressure of 0.52 Pa (Pt) and 0.35 Pa (Co). The base pressure of sputtering chamber was better than 2×10^{-6} Pa. All samples were covered by the Hall bar mask during sputtering for Hall measurement. Magnetic properties of the samples were characterized by a vibrating sample magnetometer (VSM, LakeShore Inc.) and a VersaLab system (Quantum Design, Inc.). AHE measurements were carried out from 20 to 300 K, with each sample being measured both as-deposited and after post-annealing at 100, 200, 300, 400 and 500 °C for one hour.

3. Results and conclusions

Empirically, the quality of the ferromagnetic layer would be improved after post-annealing below a critical temperature, and then takes a turn for the worse with higher annealing temperatures because of interfacial diffusion. The critical annealing temperature depends on the substrate, buffer layer, cap layer and the ferromagnetic layer itself. Fig. 1 shows a diagrammatic sketch of Co atom distribution in Pt/Co/Pt trilayers under different thermal treatments: as-deposited (a), post-annealed at low temperatures (b) and post-annealed at high temperatures (c). Hysteresis loops of Pt (2.5 nm)/Co (0.5 nm)/Pt (2.5 nm) trilayers with various annealing temperatures are shown in Fig. 1(d) as an example. It is well known that the perpendicular magnetic anisotropy (PMA) originates from the interfacial interaction in Pt/Co/Pt trilayer [21–23]. A better