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Anisotropy dependence of anomalous Hall effect in canonical spin glass alloys

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Abstract
The influence of the Dzyaloshinsky–Moriya (DM) anisotropy on the extraordinary Hall coefficient $R_s \equiv \rho_{ex}/M$, where ρ_{ex} is the extraordinary Hall resistivity and M is the magnetization, is investigated in canonical spin-glass (SG) alloys. The strength of the DM anisotropy in the alloys is changed systematically by doping with a third impurity that is non-magnetic. The Hall resistivity ρ_H, the magnetization M and the resistivity ρ were measured in the series of $(Ag_{1-x}Au_x)_{0.9}Mn_{0.1}$ alloys with $x = 0$, 0.007, 0.03, and 0.05. The difference ΔR_s between the values of zero-field-cooled and field-cooled R_s, below the SG transition temperature, clearly increased with the amount of Au impurities. The dependence of the chirality contribution to R_s on the DM anisotropy is discussed in relation to the theoretical work for the chirality-driven anomalous Hall effect in the weak coupling regime.

For many decades, the accepted parameterization of the Hall resistivity ρ_H in magnetic materials has been in terms of the canonical expression

$$\rho_H = \rho_{ord} + \rho_{ex} = R_0 H + 4\pi R_s M, \qquad (1)$$

where ρ_{ord} and ρ_{ex} are the ordinary and the extraordinary Hall resistivity respectively, R_0 and R_s are the ordinary and the extraordinary Hall coefficient respectively, H is the magnetic field and M is the magnetization. Recently, some features [1, 2] of R_s have been reported in canonical spin-glass (SG) alloys which are not understood by the conventional theory [3]. This behaviour of R_s indicates the existence of the chirality-driven extraordinary Hall effect term as predicted by the theories of the chirality mechanism of the Hall effect [4, 5]. These theories also predict that the Dzyaloshinsky–Moriya (DM) anisotropy plays an important role in the appearance of the chirality-driven extraordinary Hall effect term. The strength of the DM anisotropy of the canonical SG alloys is changed systematically by doping with a third impurity that is non-magnetic. The main purpose of the present article is to investigate how the DM anisotropy

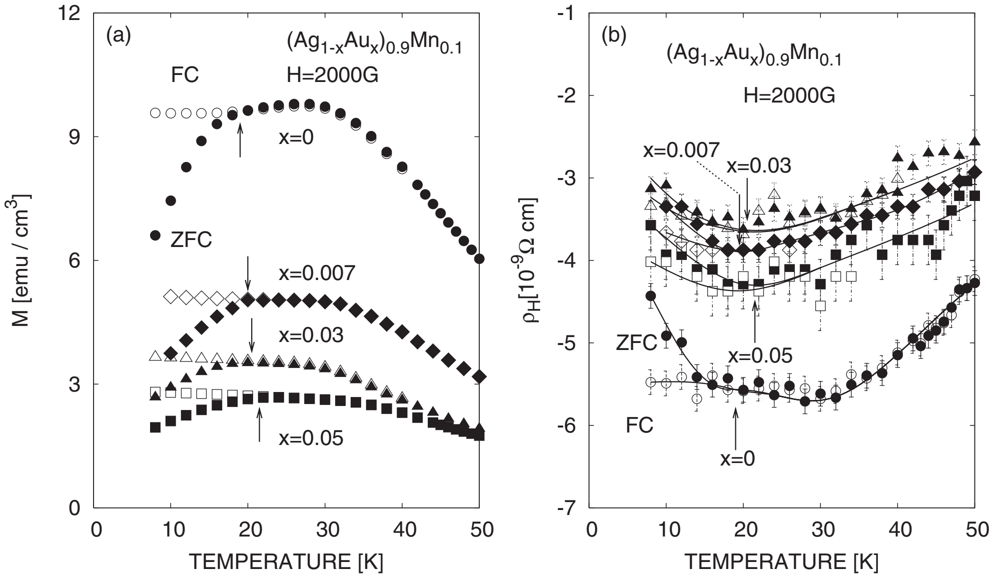

Figure 1. (a) Temperature dependence of M for $(Ag_{1-x}Au_x)_{0.9}Mn_{0.1}$ in a field of 2000 G. (b) Temperature dependence of ρ_H for $(Ag_{1-x}Au_x)_{0.9}Mn_{0.1}$ in a field of 2000 G. The arrows mark T_g (2000 G).

Table 1. d and $T_g(H)$ for $(Ag_{1-x}Au_x)_{0.9}Mn_{0.1}$.

	x			
	0	0.007	0.03	0.05
d	0.095	0.129	0.203	0.252
T_g (10 G) (K)	28.5	29.0	34.5	36.5
T_g (2000 G) (K)	19.0	20.0	20.5	21.5

act in the chirality-driven extraordinary Hall effect mechanism by simultaneously measuring ρ_H, M and the resistivity ρ for the series of AgMn alloys whose anisotropy is systematically controlled by doping with Au impurities.

The simultaneous measurement of ρ_H, M and ρ were made from 8 to 50 K in a field of 2000 G under zero-field-cooled (ZFC) and field-cooled (FC) conditions. The samples used for the measurements are $(Ag_{1-x}Au_x)_{0.9}Mn_{0.1}$ alloys with $x = 0$, 0.007, 0.03, and 0.05. The details of the measurement and sample preparation are described in [1]. Table 1 shows the SG transition temperature $T_g(H)$ and the anisotropy parameter d of the alloys. The anisotropy parameter d is defined as $d \equiv D/J$, where J and D are the exchange and anisotropy strengths respectively. The SG transition temperatures $T_g(H)$ were determined from the magnetization measurements under ZFC and FC conditions. The values of d were calculated by using the formula in [6]. The value of T_g (10 G) increases in proportion to $d^{0.8}$, which is consistent with previous studies [6].

Figure 1(a) shows the temperature dependence of M for $(Ag_{1-x}Au_x)_{0.9}Mn_{0.1}$ in a field of 2000 G [7]. The shift of T_g (2000 G) by doping Au impurities is also proportional to $d^{0.8}$. We observed that the doping has no effect on the magnitude of M in the high-temperature

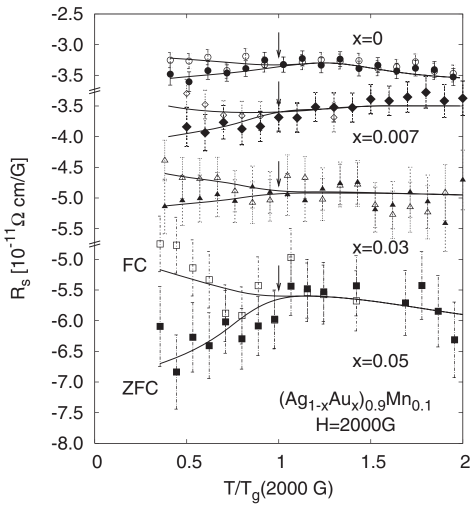

Figure 2. Temperature dependence of R_s for $(Ag_{1-x}Au_x)_{0.9}Mn_{0.1}$ in a field of 2000 G. It is noted that the temperature is divided by T_g (2000 G). The arrows mark T_g (2000 G).

region ($T \geqslant 150$ K). On the other hand, the magnitude of M around T_g (2000 G) decreases with increasing concentration of Au impurities. This behaviour may be due to mean free path effects [8]. Figure 1(b) shows the temperature dependence of ρ_H for $(Ag_{1-x}Au_x)_{0.9}Mn_{0.1}$ which was simultaneously measured with M [7]. The behaviour of ρ_H is similar to that of M, and the differences between ZFC and FC ρ_H appear below T_g (2000 G). The magnitude of ρ_H around T_g (2000 G) also decreases with Au concentration.

The Hall resistivity ρ_H is the sum of ρ_{ord} and ρ_{ex}. Extrapolations to high temperature to obtain an estimate of ρ_{ord} for the present samples indicate that R_0 is about -8×10^{-13} Ω cm G^{-1}. R_s is determined by using the value of R_0 and the ρ_H and M data.

The temperature dependence of R_s for $(Ag_{1-x}Au_x)_{0.9}Mn_{0.1}$ in a field of 2000 G is shown in figure 2. The differences ΔR_s between the values of ZFC and FC R_s in the low-temperature region (T/T_g (2000 G) <1) are observed in all samples. The difference ΔR_s clearly increases with the amount of Au impurities. In particular, ΔR_s for $(Ag_{0.95}Au_{0.05})_{0.9}Mn_{0.1}$ is as large as those of AuFe [1] and AuMn [2].

In the conventional theory [3], $R_s = A\rho + B\rho^2$, where ρ is the resistivity and A and B are constants relevant to the detailed band structure of the conduction electrons. The temperature dependence of ρ, as shown in figure 3, is monotonic even around $T/T_g(2000\text{ G}) = 1$, and the differences between ZFC and FC ρ are not observed in any samples. Therefore, the observed ΔR_s are not explained by the conventional theory.

Tatara and Kawamura have shown that the uniform chirality χ_0 contributes to the extraordinary Hall resistivity ρ_{ex} by a perturbation expansion to the weak coupling s–d Hamiltonian [4] as follows:

$$\rho_{ex} = (A\rho + B\rho^2)M + C\chi_0, \quad (2)$$

where C is a constant relevant to the detailed band structure of the conduction electrons. The uniform chirality χ_0 is the sum of the local chirality $\chi_{ijk} \equiv \boldsymbol{S}_i \cdot (\boldsymbol{S}_j \times \boldsymbol{S}_k)$ weighted by a geometrical factor which depends on the distance between the spins. Noting the geometrical factor, the contribution from χ_{ijk} of three spins on the triangle $P_i P_j P_k$ to χ_0 decays rapidly as $\sim e^{-3r/2l}/(k_F r)^3$ [4], where r is the distance, k_F is the Fermi wave number, l is the mean free

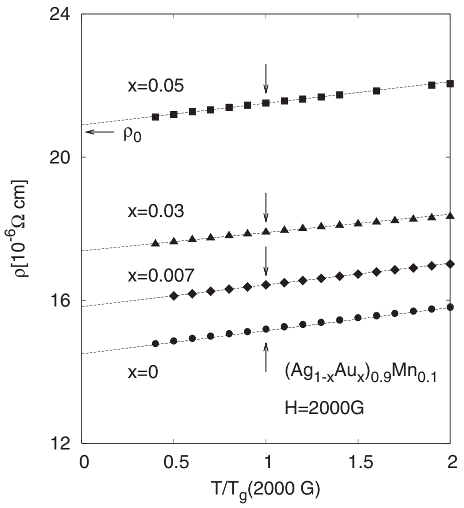

Figure 3. Temperature dependence of ρ for $(Ag_{1-x}Au_x)_{0.9}Mn_{0.1}$ in a field of 2000 G. It is noted that the temperature is divided by T_g (2000 G). The arrows mark T_g (2000 G). The dotted lines show the result of the linear fitting below 30 K. ρ_0 is the residual resistivity.

Table 2. ρ_0 and l for $(Ag_{1-x}Au_x)_{0.9}Mn_{0.1}$.

	x			
	0	0.007	0.03	0.05
ρ_0 (10^{-6} Ω cm)	15	16	17	21
l (Å)	54	51	49	39

path and P_i, P_j and P_k are the positions of $\boldsymbol{S}_i$, $\boldsymbol{S}_j$ and $\boldsymbol{S}_k$ respectively. This means that χ_{ijk} of three spins on the triangle $P_iP_jP_k$ having side-length up to l dominantly contributes to χ_0. Therefore the contribution from χ_{ijk} to the Hall effect disappears when the average distance r_{ave} between the spins is longer than l. Table 2 shows the residual resistivity ρ_0 and l for $(Ag_{1-x}Au_x)_{0.9}Mn_{0.1}$. As shown in figure 3, values of ρ_0 are determined from the extrapolation to $T = 0$ in the temperature dependence of ρ. The mean free paths l are estimated by using the value of ρ_0, assuming that collisions of the conduction electrons with impurities dominate ρ in the low-temperature region. Because $r_{\text{ave}} \simeq 6$ Å in $(Ag_{1-x}Au_x)_{0.9}Mn_{0.1}$, l is longer than r_{ave}. Therefore there are a lot of triangles $P_iP_jP_k$ having side-length up to l and the contribution from χ_{ijk} to χ_0 should appear in the present samples. However, since spins are frozen in a spatially random manner in the SG ordered state, the sign of χ_{ijk} appears randomly, which inevitably leads to the vanishing of the uniform chirality, $\chi_0 = 0$.

It thus appears that the chirality-driven extraordinary Hall effect vanishes in bulk SG sample. To examine the possible coupling between χ_0 and M, Tatara and Kawamura have looked into the effective Hamiltonian of the spin–orbit interaction H_{so}, treating s–d interaction as a perturbation. They have also shown that the effective Hamiltonian which comes from the second-order contribution contains a term $H_{\text{so}}^{(2)} \sim EM\chi_0$ [4], where E is a constant which represents the strength of the coupling between χ_0 and M. The chiral symmetry-breaking term $H_{\text{so}}^{(2)}$ guarantees χ_0 to be induced if the sample is magnetized. This means that the M is a 'chiral field' conjugate to χ_0. Then the chiral susceptibility X_χ is defined as $X_\chi \equiv \chi_0/EM$ and R_s is

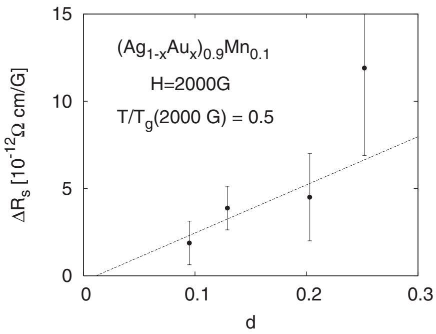

Figure 4. Anisotropy parameter d-dependence of ΔR_s for $(Ag_{1-x}Au_x)_{0.9}Mn_{0.1}$ at $T/T_g(2000\ G) = 0.5$.

represented as follows [5]:

$$R_s \equiv \rho_{ex}/M = (A\rho + B\rho^2) + CEX_\chi. \tag{3}$$

Noting the chiral symmetry-breaking term $H_{so}^{(2)}$ is essentially the DM anisotropy, two important implications of the DM anisotropy dependence of R_s are provided. First, χ_0 is not induced in the system with vanishing DM anisotropy even if the sample is magnetized. Therefore the chiral susceptibility term of R_s should vanish in the system with vanishing DM anisotropy, $CEX_\chi = 0$. Second, the strength of the coupling between χ_0 and M depends on the DM anisotropy. Therefore the chiral susceptibility term of R_s should depend on the DM anisotropy.

In our experimental results, ΔR_s, which represents the term $CE\Delta X_\chi$, clearly increases with Au concentration, where ΔX_χ is the difference between the values of ZFC and FC X_χ. Figure 4 shows the d-dependence of ΔR_s for $(Ag_{1-x}Au_x)_{0.9}Mn_{0.1}$ at $T/T_g(2000\ G) = 0.5$. One can see that $\Delta R_s \sim 0$ when $d = 0$ and ΔR_s is roughly proportional to d. According to the theoretical prediction by Tatara and Kawamura [4], this observation indicates that the DM anisotropy acts as a 'chiral symmetry-breaking field' inducing χ_0 in the presence of M, which results in the chirality-driven extraordinary Hall effect in canonical SG alloys.

References

[1] Taniguchi T, Yamanaka K, Sumioka H, Yamazaki T, Tabata Y and Kawarazaki S 2004 *Phys. Rev. Lett.* **93** 246605

[2] Pureur P, Wolff Fabris F, Schaf J, Vieira V N and Campbell I A 2004 *Europhys. Lett.* **67** 123

[3] Kaplus R and Luttinger J M 1954 *Phys. Rev.* **95** 1154

[4] Tatara G and Kawamura H 2002 *J. Phys. Soc. Japan* **71** 2613

[5] Kawamura H 2003 *Phys. Rev. Lett.* **90** 047202

[6] Fert A, de Courtenay N and Bouchiat H 1988 *J. Physique* **49** 1173

[7] Yamanaka K, Taniguchi T, Yamazaki T and Kawarazaki S *Proc. 24th Int. Conf. on Low Temperature Physics* (*AIP Conf. Proc.* 850) to be published

[8] Jagannathan A, Abrahams E and Stephem J M 1987 *Phys. Rev.* B **37** 436