Journal of Korean Magnetics Society, Volume 5, Number 6, December 1995

ANOMALOUS HALL EFFECT IN AMORPHOUS $Fe_{0.33}Zr_{0.67}$ ALLOY

K. Rhie
Department of Physics, Korea University
Chochiwon, Chungnam, 339-700 Korea

D. G. Naugle
Department of physics, Texas A&M University
College Station, Tx77843-4242

(Received 22 August 1995)

Abstract-It is well kown that the side-jump effect, originated from the spin-orbit scatterring of the transport electrons at the site of spin-orbit scatterers, is the reason for the anomalous Hall resistivity which is proportional to the magnetization. Our recent magnetization study implied that abundant ferromagnetic Fe clusters made of for Fe ions dominate the temperature and field dependence of magnetization at high field and low temperature regime for a paramagnetic $Fe_{0.33}Zr_{0.67}$ alloy. We measured the Hall resistivity of this alloy and observed that the Hall resistivity followed the M-H curve at low temperature, and the Hall coefficients at moderate temperatures were proportional to the magnetic susceptibility. We explain the behavior of Hall resistivity with the change of field and temperature in terms of side-jump effect.

I .INTRODUCTION

Anomalous Hall effect, specially, the side jump effect has been well accepted for the reason of the non-linear Hall resistivity [1-3] which is not proportional to the magnetization of the samples in ferromagnetic materials. It has been assumed that the side jump effect in paramagnetic amorophous materials is much weaker than the Lorentz term, since the magnetization in paramagnetic phase is too small. The Hall resistivity including the side-jump effect term can be written as

$$\begin{aligned}\rho_H &= \frac{V_H \cdot d}{I} \\ &= \mu_o R_o(H_a - NM) + \mu_o R_1 M \\ &= R_o B_a + \mu_o M(R_1 - R_o N) \\ &= R_o B_a + \mu_o M R_s \quad \cdots \quad (1)\end{aligned}$$

where ρ_H, V_H mean the Hall resistivity and voltage, R_0, R_s represent normal and spontaneous Hall coefficientcent, respectively. The spontaneous part can be rewritten as

$$\begin{aligned}\rho_H^{SJ} &= \rho^2 \sigma_{xy}^{SJ} \\ &= \sum_i \frac{2\rho^2 N_i q_i^2}{\hbar} \lambda_{SO}^{SJ} \langle S_z \rangle) \qquad (1)\end{aligned}$$

$$\text{with } \lambda_{SO}^{SJ} = \sum_n \frac{|\langle n | \overrightarrow{L} | 0 \rangle|^2}{\varepsilon_n - \varepsilon_F} I\, l^2 A_{SO} \ ,$$

where i denotes carrier type, q_i denotes charge of i-type carrier, λ_{SO}^{SJ} denotes the effective spin-orbit parameter A_{SO} is the atomic spin-orbit parameter, I is the overlap integral and l is the distance between the scatterers. Therefore, the spontaneous Hall resistivity is proportional to the magnetization, square of resistivity and λ_{SO}^{SJ}.

Recent works on the Hall coefficient (R_H) for paramagnetic amorphous materials, however, showed that this side jump effect is also important in the paramagnetic phase [4-5]. Trudeau et. al. showed that the temperature dependence of Hall coefficient is proportional to the magnetic susceptibility in paramagnetic phase near the onset of ferromagnetic state [4]. Rhie et. al. showed that the curious concentration dependence of R_H for amorphous late transition metals-Zr alloys can be qualitatively explained on the basis of the side-jump effect [5]. The most dramatic evidence that the side jump effect is dominant paramagnetic amorphous alloys is the sign change of R_H with temperature of an amorphous $Ni_{0.70}Cr_{0.10}P_{0.20}$ alloy [6]. R_H of this alloy increased with magnetic susceptibility as the temperature decreases, from a negative value at room temperature and changed its sign to positive around 20 K.

The temperature dependence of Hall coefficient proportional to the that of magnetization, or susceptibility in paramagnetic phase [4]. In this experiment, we repeated the measurement of Hall coefficients with temperature for one of the sample ($Fe_{0.33}Zr_{0.67}$) that Trudeau et. al. reported before[4]. We studied at a lower temerature than they did, and also, the magnetization study for this alloy is published else where [7]. In this magnetization study, we found something unexpected. The $Fe_{0.33}Zr_{0.67}$ is no longer Pauli paramagnetic, and showed that some ferromagnetic clusters of small Fe-ions saturate at low temperature (4.6 K) around applied field of 1 T, implying that these clusters produce an extra magnetization that follows the Langevin function. The authors concluded that the abnormal temperature dependence of magnetic suceptibility in paramagnetic amorphous $Fe_{0.33}Zr_{0.67}$ is caused by these nanoparticles with the average local moments of $15\mu_B$. These particles did not saturate up to 1 T at higher temperatrures, since the local moments are too small to be saturated. Of course, at high temperature limit, these particles follow Curie's law.

The cause of this experiment is to see the saturation behavior of hall resistivity at low enough temperature and compare it with the magnetization data.

II.EXEPERIMENT

About 5mm wide $Fe_{0.33}Zr_{0.67}$ alloy was melt spun at an Ar atmosphere through a wide and thin nozzle. 5 probe dc method was used to measure the Hall resistivity.

It is well known that spot welding causes partial crystallization to the sample, and it causes larger and unwanted signal when current passes through heated region, specially for paramagnetic alloys near ferromagnetic phase or ferromagnetic alloys. In order to avoid any unwanted effect of partial crystallization that could be caused in the spot-welding process, we cut the sample partially along the lengthwise direction for three Hall contacts, hinged them off and spot-welded thin copper wires on them as shown in Fig. 1. When current flows along the lengthwise direction, it does not flow to the hinges, so that one can eliminate the effect of partial crystallization by spot-welding process.

Magnetic field was varied -5 to 5 T using a superconducting magnet, and the temperature was controlled using a PID temperature controller.

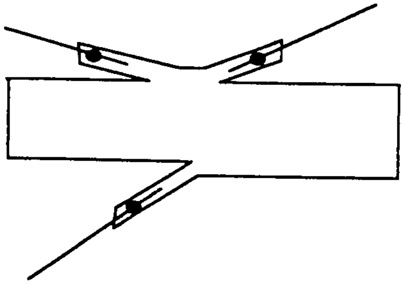

Fig. 1 Diagram of spot welding contact to the ribbon.

III.RESULTS AND DISCUSSION

The temperature dependence of R_H in Fig. 2 is same to the results of Cocrane et. al. [4], except the data point at 4.6 K, where we already reported that a saturation of magnetization occured [7]. The Hall coefficients follows a Curie-Weiss curve that represents paramagneic susceptibility of a paramagnetic material.

The Hall resistivity at 4.6 K is nonlinear with H, as shown in the Fig. 3. The open circles in Fig. 2 represents the R_H (linear fit of Hall resistivity with H) at all temperatures and circle at 4.6 K represents the slope in high field as marked in Fig. 3. One should note that the Hall resistivity in Fig. 3 is linear with T at 10 K and becomes nonlinear at 4.6 K. This Curious behavior of Hall resistivity was also reported earlier for other Fe-Zr alloy near ferromagnetic phase [9]. But magnetization study was not done to analize the Hall resistivity together. We introduce our magnetization study [7] briefly, and try to connect it with this Hall effect data. Since M or $\langle S_z \rangle$ is the only temperature dependent factor in Eq. 1 and 2, it is worth to compare Fig. 2 and the temperature dependence of magnetic susceptibility [7] as shown in Fig. 4.

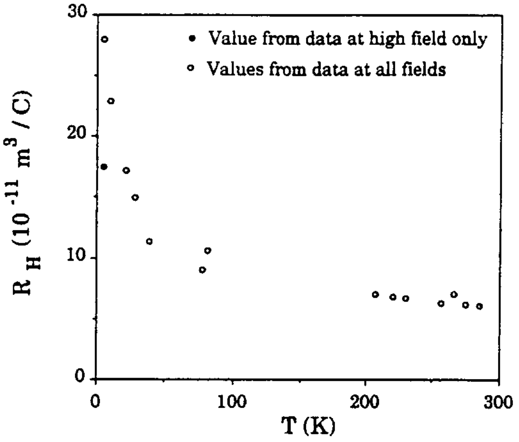

Fig. 2 Temperature dependence of R_H. The Hall coefficients (•) calculated with the data at all fields is different from the one (•) determined from the linear portion of the high field data in Fig. 3

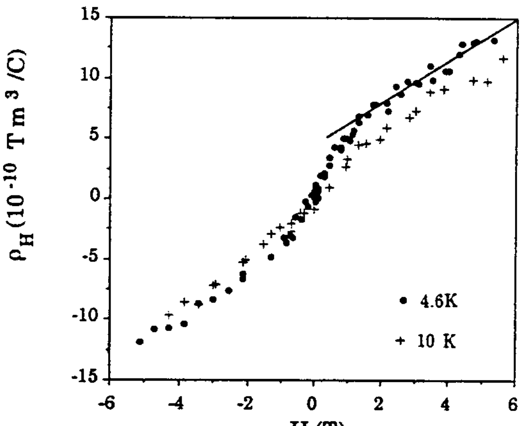

Fig. 3 Hall resistivity at 4.6 and 10 K for $Fe_{0.33}Zr_{0.67}$ alloy. Note that the Hall resistivity at 10 K is linear with applied field H.

Also, the field dependent Hall resistivity (Fig. 3) needs to be compared with the magnetization (Fig. 5).

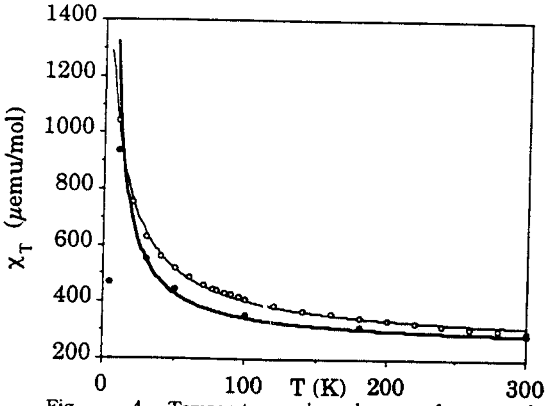

Fig. 4 Temperature dependence of magnetic susceptibility for $Fe_{0.33}Zr_{0.67}$ alloy. The total magnetic susceptibility (∘) follows Curie-Weiss law (thin line), and the high field magnetic susceptibility (•) follows Curie's law above 10 K.

The circles and solid circles in the figure represents the total magnetic susceptibility and high field susceptibility respectively. Total magnetic susceptibility follows Curie-Weiss law, and the high field susceptibility follows Curie law above 10 K. It however, droped at 4.6 K to the half of that at 10 K. Rhie et. al. [7] explained that the reason for this sudden drop is because 10 K is the limit where the Curie approximation of Langevin function for additional magnetization caused by few Fe-ion clusters. In other words, the field dependence of magnetization caused by small clusters made of few Fe ions is no longer linear with H and follows the Langevin function as shown in Fig. 5.

Clearly, this saturation of magnetization at 4.6 K is proportional to the nonlinear Hall resistivity at the same temperature, as expected from Eq. 2.

As a conclusion, we observed a temperature dependent Hall effect in paramagnetic $Fe_{0.33}Zr_{0.67}$ alloy, near ferromagnetic phase, and a nonlinear Hall resistivity with H at a low temperature. These observed results are compared with the magnetization measurments, which suits well with the theory of side jump effect.

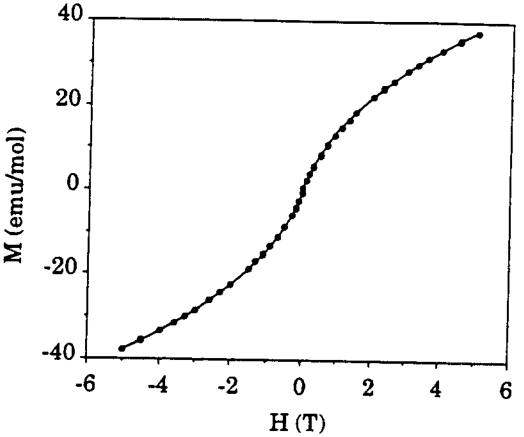

Fig. 5 M vs H diagram for $Fe_{0.33}Zr_{0.67}$ alloy at 4.6 K. Note the saturation of local moments around 1 T. The line is a langevin function fit.

REFERENCES

[1] T. R. Macguire, R. J. Gambino, and R. C. O'Handley, in the *The Hall effect and its applications*, edited by C. L. Chien and C. L. Westgate (Plenum, New York, 1980), P. 137

[2] L. Berger and G. Bergmann, *ibid* p. 55

[3] L. Berger Phys. Rev. **B22**, 4559 (1970)

[4] M. L. Trudeau, R. W. Cochrane, D. V. Baxter, J. O. Strom-Olsen, and W. B. Muir, Phys. Rev. **B45**, 5066 (1992)

[5] K. Rhie, D. G. Naugle, Beom-hoan O, J. T. Markert, Phys. Rev. **B48**, 5973 (1993)

[6] K. Rhie, D. G. Naugle, Beomhoan O, J. T. Markert, Phys. Rev. **B49**, 12688 (1994)

[7] K. Rhie, D. G. Naugle, Beomhoan O, J. T. Markert, J. Phys.: Condensed Matter 7 3315 (1995)

[8]K. Rhie, *Thesis for his Ph. D degree at Texas A&M University, USA*

[9] R. W. Chochrane, M. Trudeau, and J. O. Strom-Olsen, J. Appl, Phys, 57 (1), 3207 (1985)