Hall effect in crystalline Ni-Fe-Cr alloys showing resistivity minima

S. Chakraborty and A. K. Majumdar*
Department of Physics, Indian Institute of Technology, Kanpur 208016, Uttar Pradesh, India
(Received 8 September 1997)

The temperature dependence of Hall resistivity (ρ_H) is presented for magnetic inductions up to 1.3 T and temperatures down to 1.4 K. The samples are ferromagnetic Ni-rich γ-$Ni_{75}Fe_{13}Cr_{12}$ (sample 1), $Ni_{70}Fe_{12}Cr_{18}$ (sample 2), and $Ni_{73.5}Fe_8Cr_{18.5}$ (sample 3) alloys. The values of the ordinary (R_0) and the extraordinary (R_s) Hall coefficients are found to be positive in samples 2 and 3 whereas they are negative in sample 1. Electrical-resistivity $[\rho(T)]$ studies in these alloys have shown resistivity minima (at $T_{\min}$) that are described by electron-electron interaction effects. R_0 is found to be nearly temperature independent in all the alloys. On the other hand, $R_s(T)$ has shown minima, very similar to those of $\rho(T)$ around $T_{\min}$. The temperature dependence of the positive extraordinary Hall coefficient in samples 1 and 3 is consistent with the minima observed in $\rho(T)$, whereas the negative extraordinary Hall coefficient in sample 1 behaves exactly opposite to what is expected theoretically, i.e., instead of getting more negative, the coefficient becomes more positive on both sides of $T_{\min}$. This is found to be rather puzzling and cannot be explained in terms of the existing theories. However, the positive $R_s(T)$ is interpreted indirectly (through their electrical resistivity) by electron-electron interaction effects. [S0163-1829(98)00119-2]

The Hall resistivity in any ferromagnetic material[1] well below its Curie temperature (T_c) is usually expressed as $\rho_H = R_0 B_z + R_s M_s$, where R_0 is the ordinary Hall coefficient (OHC), R_s the extraordinary Hall coefficient (EHC), B_z the magnetic induction, and M_s the saturation magnetization. The origin of $R_0 B_z$ is the Lorentz force acting on the conduction electrons whereas the second term is attributed to the spin-orbit interaction[1,2] present in a ferromagnet. The values of $R_s M_s$ and R_0 are obtained from the intercept and the slope, respectively, of a linear fit of the Hall data beyond saturation. Theoretically, the concentration as well as the temperature dependence[1–3] of R_s is given by $R_s = K\rho^n$, where $n=1$ (skew scattering) and 2 (side-jump effect), and K is a proportionality constant. The skew scattering ($R_s = K\rho$) is expected only in pure metals and dilute alloys[1,3] at low temperatures and the side-jump effect ($R_s = K\rho^2$) is dominant in concentrated[1,2] alloys where ρ is large (i.e., $\rho_H \ll \rho$). Interestingly, until now most of the studies[1–6] in crystalline alloys were focused on the concentration dependence of the EHC, whereas its temperature dependence has not been paid much attention. Recently, some precise measurements of the Hall effect have clearly shown in nonmagnetic CuTi and CuZr amorphous alloys[7–9] that R_0 decreases slowly with temperature. The presence of dominant electron-electron interaction effects (EEI) in the weak-localization limit[10] is considered to be its cause. Here we have presented high-resolution Hall-effect data up to 1.3 T in Ni-rich γ-$Ni_{75}Fe_{13}Cr_{12}$ (sample 1), $Ni_{70}Fe_{12}Cr_{18}$ (sample 2), and $Ni_{73.5}Fe_8Cr_{18.5}$ (sample 3) alloys at several temperatures in the range of 1.4–80 K, 1.4–186.3 K, and 1.4–30.3 K, respectively. The present alloys are all ferromagnetic[11,12] with T_c's at 365, 179, and 44 K, respectively. Also, they are compositionally disordered with large residual resistivity[11] values ($\rho_0 \simeq 100\ \mu\Omega$ cm). The electrical resistivity $[\rho(T)]$ study in these alloys has shown resistivity minima.[11] The motivation behind the present investigation is to find the temperature dependence of the EHC in the present crystalline ferromagnetic alloys that show resistivity minima.

A specially designed cryostat is used for electrical resistivity, magnetoresistance, and Hall-effect measurements. A standard four-probe dc technique is used with a 250 mA sample current. In the flat Hall sample (20 mm $\times$3 mm$\times$0.15 mm), the magnetic induction B inside it is very nearly the same as $\mu_0 H$ (where H is the external field) since the demagnetization factor α is almost equal to 1 $[B = \mu_0 H + \mu_0(1-\alpha)M_s]$. The temperature stability is better than 0.1 K below 20 K and 0.2 K above it. Here the total Hall signal is found in the range of 2–3 μV with the misalignment voltage of the order of 1 μV at 1.3 T and 1.4 K. The experimental resolution of the present data is better than 0.5%.

In Fig. 1, the $\rho(T)/\rho(T_{\min})$ data up to 40 K are shown for sample 3, sample 2, and sample 1 alloys. All the details of the alloy composition, T_c, $\rho_{1.2\ \mathrm{K}}$, $T_{\min}$, depth of minima $[=\rho(1.2\ \mathrm{K}) - \rho(T_{\min}/\rho(1.2\ \mathrm{K})]$, and $\Delta\rho/\rho_{290\ \mathrm{K}}$ are given in Table I. The $\rho(T)$ data are interpreted[11] in terms of the electron-magnon scattering (BT^2) along with the EEI effects[10] ($-m_\rho\sqrt{T}$) in the temperature range 1.2–30 K. Typical ρ_H vs magnetic induction data are shown in Figs. 2 and 3 for sample 2 and sample 1, respectively, at some selected temperatures for better clarity. The absolute value of ρ_H beyond saturation for sample 3, sample 2, and sample 1 exhibit a decrease with increasing temperature (see Figs. 2 and 3). ρ_H is found to be positive for both sample 3 and sample 2, whereas it is negative for sample 1. The sign of the OHC and $R_s M_s$ are found to be positive in both sample 2 and sample 3, whereas they are negative in sample 1. It is very interesting to note from Table I that ρ_H beyond saturation at 1.4 K are three orders of magnitude smaller than the residual resistivity (ρ_0) in all the alloys. The values of the OHC are of the same order as observed earlier in dilute crystalline FeCr and FeCo alloys.[4] The values of the EHC (R_s),

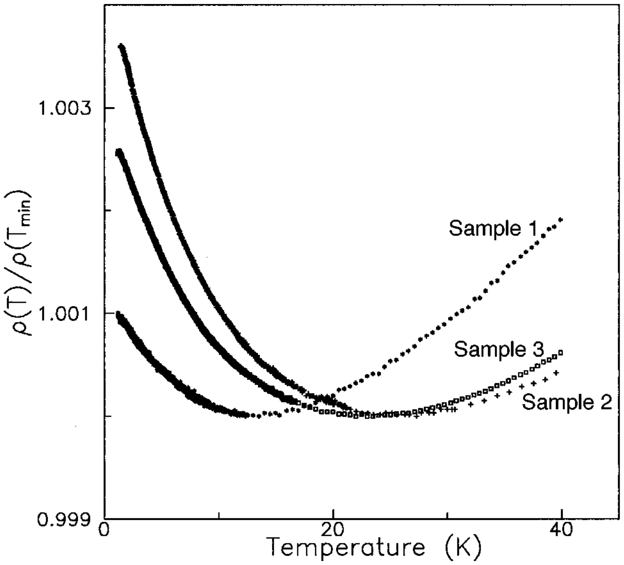

FIG. 1. Plot of the resistivity normalized to its value at $T_{\min}$ vs temperature up to 50 K for sample 1, sample 3, and sample 2.

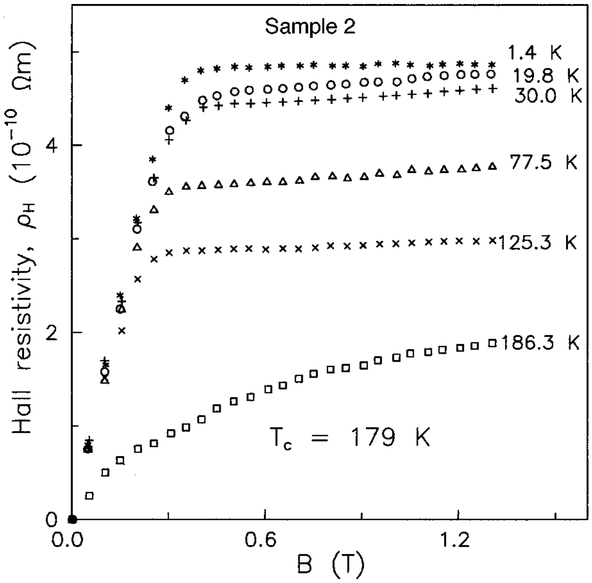

FIG. 2. Plot of the Hall resistivity (ρ_H) for sample 2 in magnetic fields up to 1.3 T at 1.4, 19.8, 30.0, 77.5, 125.3, and 186.3 K.

evaluated from $R_s M_s$ and $M_s(T)$,[12] are two orders of magnitude greater than those of the OHC. However, they are an order of magnitude greater than those of the dilute crystalline FeCr alloys[4] and nearly equal to those of the concentrated Ni-rich NiCu alloys.[13] The Hall resistivity (ρ_H) beyond saturation is almost equal to $R_s M_s$, i.e., $\rho_H \simeq R_s M_s$ (see Table I). Hence, theoretically, such a large extraordinary contribution[1–3] to ρ_H can certainly be attributed to the side-jump effect.

The temperature dependence of the OHC (R_0) is shown in Fig. 4 where it is found to be almost a constant except for a broad maximum. On the other hand, the temperature dependence of EHC in the present alloys, irrespective of their sign, exhibits (see Fig. 5) a nature very similar to those of $\rho(T)$. In Fig. 5, the data for sample 2 are shown up to 80 K whereas those for sample 3 and sample 1 are presented up to 40 K. The $R_s(T)$ for sample 3, sample 2, and sample 1 has shown minima at 20, 35, and 20 K, respectively, which are of the same order as the $T_{\min}$ of their resistivity. However, the decrease in R_s up to their respective minima are found around 11, 7, and 1% for sample 3, sample 2, and sample 1, respectively, which are quite large compared to the depth of the minima (see Table I) of their $\rho(T)$. Recently, large changes in the Hall coefficient as compared to those of the electrical resistivity have been observed in some highly resistive alloys.[9,14] In conventional ferromagnetic crystalline metals and alloys,[1,3,4,15] $\rho(T)$ is generally found to increase with temperature which, in turn, increases the magnitude of the EHC ($R_s = K\rho^n$). As a result, with increasing temperature, the positive EHC becomes more positive[4,15] (e.g., Fe) and the negative EHC more negative[15] (e.g., Ni). Here, in Fig. 5, one finds that the temperature dependence of the positive EHC in sample 3 and sample 2 is consistent with the minima of the $\rho(T)$ data. On the contrary, the negative EHC in sample 1 shows a behavior exactly opposite to what is expected. As the resistivity increases below as well as above $T_{\min}$, the negative EHC, instead of becoming more negative on both sides of $T_{\min}$, becomes less negative. In other words, the R_s vs T plot of sample 1 should have been a mirror image about the temperature axis of sample 3 and sample 2. This is found to be rather puzzling. A similar behavior had been observed in pure Co where the negative EHC shows a

TABLE I. Sample designation with their composition, ferromagnetic Curie temperature (T_c), $T_{\min}$, value of resistivity at 1.2 K ($\rho_{1.2\ \mathrm{K}}$), depth of minimum, $\Delta\rho/\rho_{300\ \mathrm{K}}$ ($\Delta\rho = \rho_{300\ \mathrm{K}} - \rho_{\min}$) along with values of Hall resistivity (ρ_H) beyond saturation, $R_s M_s$, R_s, and R_0 at 1.4 K.

Sample no. Alloy composition	Sample 1 $Ni_{75}Fe_{13}Cr_{12}$	Sample 2 $Ni_{70}Fe_{12}Cr_{18}$	Sample 3 $Ni_{73.5}Fe_8Cr_{18.5}$
T_c (K)	365	179	44
$T_{\min}$ (K)	14	22	27
$\rho_{1.2\ \mathrm{K}}$ (10^{-8} Ωm)	89.6	71.8	76.0
Depth of minima (%)	0.10	0.26	0.37
$\Delta\rho/\rho_{290\ \mathrm{K}}$ (%)	4.9	3.8	3.2
ρ_H (10^{-10} Ωm)	−13.7	4.8	3.2
$R_s M_s$ (10^{-10} Ωm)	−13.10 (±0.03)	4.70 (±0.02)	2.80 (±0.01)
R_0 (10^{-11} Ωm T^{-1})	−4.9 (±0.3)	1.1 (±0.1)	4.2 (±0.4)
R_s (10^{-9} Ωm T^{-1})	−2.70 (±0.01)	1.60 (±0.01)	2.30 (±0.01)

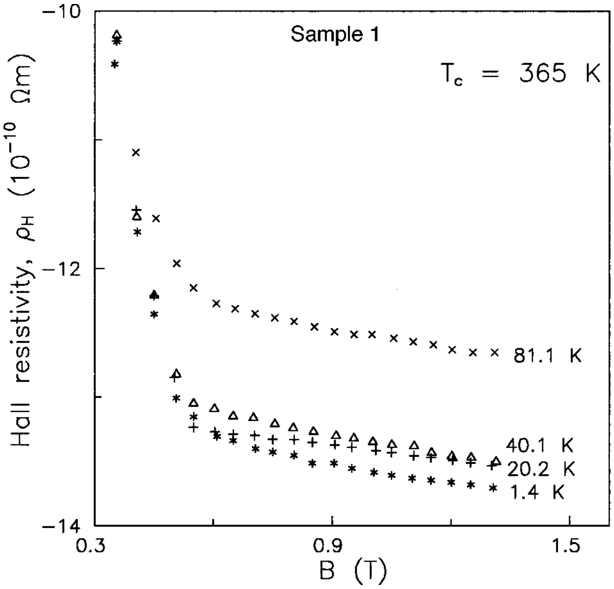

FIG. 3. Plot of the Hall resistivity (ρ_H) for sample 1 in magnetic fields of 0.3 to 1.3 T at 1.4, 20.2, 40.1, and 81.1 K.

minimum at 80 K and finally it becomes positive at room temperature.[15] This cannot be explained by the usual scattering mechanisms ($R_s = K\rho^n$). Using the earlier interpretation[11] of the $\rho(T)$ data $[\rho(T) = \rho_0 - m_\rho\sqrt{T} + BT^2$, where ρ_0 is the residual resistivity], the temperature dependence of the EHC can be written as (assuming side-jump mechanism)

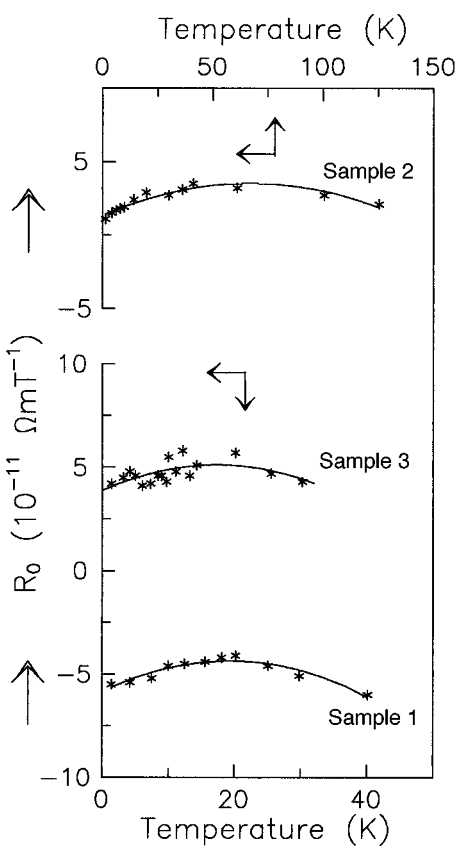

FIG. 4. Plot of the temperature dependence of the OHC (R_0) for sample 2, sample 3, and sample 1.

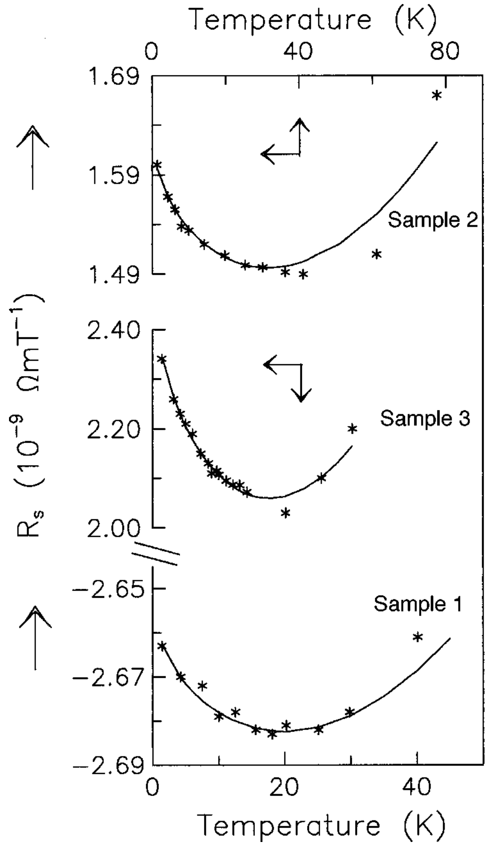

FIG. 5. Plot of the temperature dependence of the EHC (R_s) and their fits to Eq. (1) for sample 2 and sample 3. For sample 1, see text.

$$R_s(T) = K[\rho(T)]^2$$
$$\simeq R_s^0 - m_H\sqrt{T} + B_H T^2$$
$$\text{(neglecting higher-order terms)}, \qquad (1)$$

where $R_s^0 = K\rho_0^2$, $m_H = 2K\rho_0 m_\rho$, and $B_H = 2K\rho_0 B$. Here the term $R_s^0 = K\rho_0^2$ can be called the residual EHC that is solely dependent on the composition of the alloy. The data for the positive EHC gives a very good fit to Eq. (1) in the temperature range of 1.4–40 K that can be seen from Fig. 5. The values of the normalized χ^2 $\{1/N\Sigma_{i=1}^{N}[(\text{raw})_i - (\text{fit})_i]^2/(\text{fit})_i^2\}$, obtained from the fittings, are of the order of 3×10^{-5}, which is close to our experimental resolution. In Fig. 5, the best-fitted curves for sample 3 and sample 2 are extrapolated to show deviations at higher temperatures. The values of R_s^0 for sample 2 and sample 3, obtained from the fittings, are coming as 1.64 and 2.52 (all are in 10^{-9} Ω mT^{-1}), respectively. On the contrary, the values of m_H (in the units of 10^{-11} Ω mK$^{-1/2}$ T^{-1}) and B_H (in the units of 10^{-14} Ω mK^{-2} T^{-1}) are found to be 3 and 5, and 15 and 49 for sample 2 and sample 3, respectively. The values of m_ρ and B, calculated from the fitting parameters m_H and B_H of Eq. (1), are found to be an order of magnitude higher than those obtained from the fitting of the $\rho(T)$ data. The large changes in $R_s(T)$, up to their minima compared to those of $\rho(T)$, is likely to be the main reason for such deviations. Moreover, this is not unexpected, as these values are obtained from two different experiments and especially the $R_s(T)$ data are extracted out of the very small Hall voltages. Thus the minima in the positive $R_s(T)$ can certainly be attributed indirectly [through $\rho(T)$] to the dominant presence of the EEI effects. On the other hand, as mentioned earlier, the minimum in the negative $R_s(T)$ for sample 1 cannot be similarly interpreted since it should have shown a maximum instead. However, the best-fitted line (that has no physical significance) through the experimental data is shown for sample 1 in Fig. 5 only to demonstrate the minimum. Nonetheless, this shows clearly that the dispersion in the present EHC $[R_s(T)]$ data is less than 0.5%. To the best of our knowledge, this is the only paper where such strong minima in the EHC are found for any concentrated crystalline ferromagnet.

Financial assistance from Project No. SP/S2/M-24/93 of The Department of Science and Technology, Government of India and NSF Grant No. INT-9602975 is gratefully acknowledged.

*Author to whom correspondence should be addressed. Electronic address: akm@iitk.ernet.in

[1] L. Berger and G. Bergmann, in *The Hall Effect and Its Applications*, edited by C. L. Chien and C. R. Westgate (Plenum, New York, 1980), p. 55.

[2] L. Berger, Phys. Rev. B **32**, 4559 (1970).

[3] T. R. McGuire, R. J. Gambino, and R. C. O'Handley, in Ref. 1, p. 137.

[4] A. K. Majumdar and L. Berger, Phys. Rev. B **7**, 4203 (1973).

[5] H. Ashworth, D. Sengupta, G. Schnakenberg, L. Shapiro, and L. Berger, Phys. Rev. **185**, 172 (1969).

[6] A. K. Gangyopadhyay, R. K. Ray, and A. K. Majumdar, Phys. Rev. B **30**, 1801 (1984).

[7] B. L. Gallagher, D. Greig, and M. A. Howson, J. Phys. F **14**, L225 (1984).

[8] M. A. Howson and B. L. Gallagher, Phys. Rep. **170**, 265 (1988).

[9] A. Schulte, W. Haensch, G. Fritsch, and E. Lüscher, Phys. Rev. B **40**, 3581 (1989).

[10] B. L. Altshuler, A. G. Aronov, A. I. Larkin, and D. Khmel'nitskii, Zh. Eksp. Teor. Fiz. **81**, 768 (1981) [Sov. Phys. JETP **54**, 411 (1981)].

[11] S. Chakraborty and A. K. Majumdar, J. Magn. Magn. Mater. (to be published).

[12] A. K. Majumdar, K. D. D. Rathnayaka, and D. G. Naugle (unpublished); A. K. Gangyopadhyay, R. K. Ray, and A. K. Majumdar, Phys. Rev. B **30**, 6693 (1984).

[13] S. N. Kaul, Phys. Rev. B **20**, 5122 (1979).

[14] D. Müller, J. W. Schünemann, and K. Bärner, J. Magn. Magn. Mater. **110**, 161 (1991).

[15] N. V. Volkenshtein and G. V. Fedorov, Zh. Eksp. Teor. Fiz. **38**, 64 (1960) [Sov. Phys. JETP **11**, 48 (1960)].