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Citation: Journal of Applied Physics **53**, 8240 (1982); doi: 10.1063/1.330338
View online: http://dx.doi.org/10.1063/1.330338
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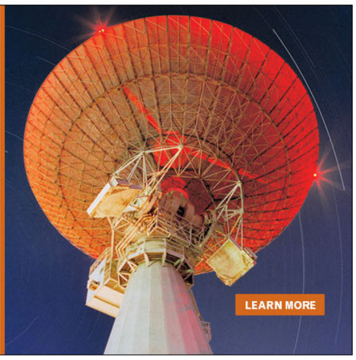

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Resistivity and galvanomagnetic coefficients of iron group metallic glasses with chromium substitutions

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Magnetic field and temperature dependences of the electrical resistivities and Hall resistivities were measured for the metallic glass ferromagnets $Fe_{13}Ni_{60}Cr_5Si_{10}B_{12}$, $Fe_{37}Ni_{36}Cr_5Si_{10}B_{12}$, $Fe_{81}B_{13.5}Si_{3.5}C_2$, and $Fe_5Co_{75}Si_{15}B_5$. Resistance minima and magnetoresistivity of the FeNiCr glasses have been found to be consistent with a modified Kondo model of low temperature scattering. The Hall resistivities are positive and large. The spontaneous Hall coefficients of the FeNiCr glasses are in good agreement with previous magnetization measurements on the same glasses.

PACS numbers: 72.15. – v, 75.30. – m

INTRODUCTION

Magnetic and electrical properties of amorphous ferromagnets have been of recent interest [1-4]. These materials have high resistivities, with small temperature coefficients of either sign, and resistivity minima have been observed at low temperatures. Explanations of these minima have been proposed on the basis of a structural model [5], and a Kondo-type model [6]. Unusually large ordinary and anomalous Hall coefficients have been observed [3].

Magnetic, electrical and structural properties of six compositions of the glass $(Fe_{1-x}Ni_x)_{78-y}Cr_ySi_{10}B_{12}$ were reported previously [7,8]. This report continues and broadens that investigation. Here the galvanomagnetic properties of the four metallic glasses $Fe_{13}Ni_{60}Cr_5Si_{10}B_{12}$, $Fe_{37}Ni_{36}Cr_5Si_{10}B_{12}$, $Fe_{81}B_{13.5}Si_{3.5}C_2$ (Allied 2605SC) and $Fe_5Co_{75}Si_5B_{15}$ are examined over a range of temperatures. Subsequently, we denote these four compositions as Fe13, Fe37, Fe81 and Fe5Co75.

EXPERIMENTAL

The Fe13 and Fe37 glasses were produced by splat cooling and had a nonuniform thickness 30-80 μ. The Fe81 Metglas was melt-spun by Allied Corporation and had a nearly uniform thickness of 50 μ. The Fe5Co75 was also melt-spun [9] and had a nearly uniform thickness of 38 μ. In Fe37 a substantial variation in sample thickness was observed. In both FeNiCr glasses there were surface irregularities. These dimensional uncertainties limit the accuracy of the Hall resistivity measurements and may affect the ratio $\Delta\rho(H)/\rho(0)$, as inhomogeneities may give unstable current distributions in a field H.

The resistivities were measured by a d.c. four-point field reversal technique with mechanical contacts. A magnetic field up to 10 kOe was applied parallel and perpendicular to the foil plane but always transverse to the current direction. Temperatures ranged from 4.2 K to 295 K.

RESULTS & DISCUSSION

Fe13, a ferromagnet with a Curie temperature around 120 K, was found to have a resistivity minimum at 39 K. Similar behavior was observed in Fe37 which has $T_c \simeq 600$ K and $T_{min} \simeq 65$ K. A logarithmic temperature dependence below the minimum is shown in Fig. 1 for Fe13. This is predicted by both the structural [5] and magnetic Kondo-type models [6]. The temperature dependence of resistivity of Fe13 and Fe37 in a magnetic field is shown in Fig. 2 and Fig. 3. The negative magnetoresistance is much larger in Fe13 than in Fe37. The field shifts the resistivity curves without affecting their temperature dependence. The field dependent shift suggests that the scattering is of magnetic, not structural [10], origin. Insensitivity of the temperature dependence to fields does not rule out spin-flip

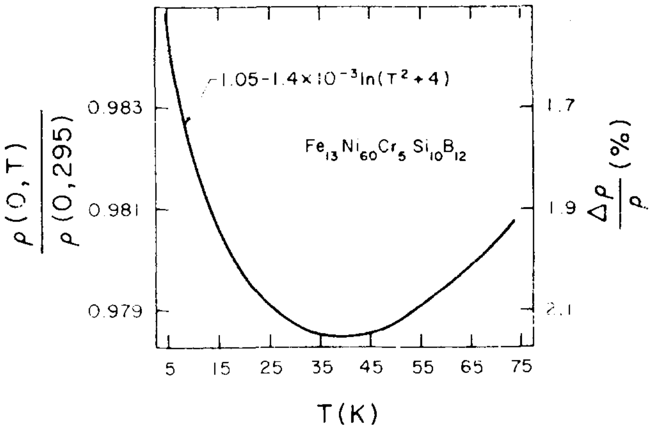

Fig. 1. Temperature dependence of the electrical resistivity of Fe13 in zero field. Note the logarithmic increase below the 39 K minimum.

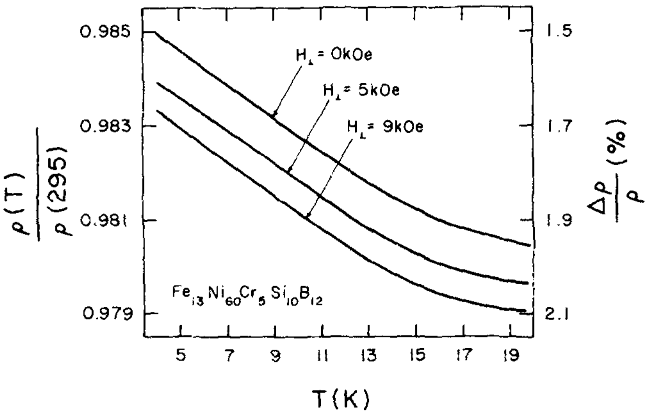

Fig. 2. Temperature dependence of the electrical resistivity of Fe13 in the logarithmic region, with applied transverse fields. The logarithmic term is not changed by the field from that of Fig. 1.

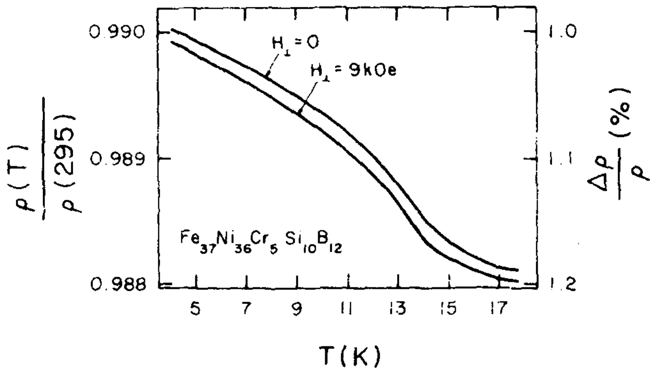

Fig. 3. Temperature dependence of the electrical resistivity of strongly ferromagnetic Fe37 below the 65 K minimum, with applied transverse fields. The temperature dependence is not field dependent.

scattering if the distribution p(H) of effective internal field extends through zero to negative fields [6]. Spins near zero give rise to spin-flip scattering. A magnetic field will shift the distribution to higher fields, but not strongly affect the spin-flip scattering. This is consistent with high-field susceptibility and magnetoresistance measurements.

The transverse magnetoresistance in Fe37 is typically ferromagnetic (Fig. 4). With field parallel to the foil, demagnetizing fields are small and saturation is reached at lower fields.

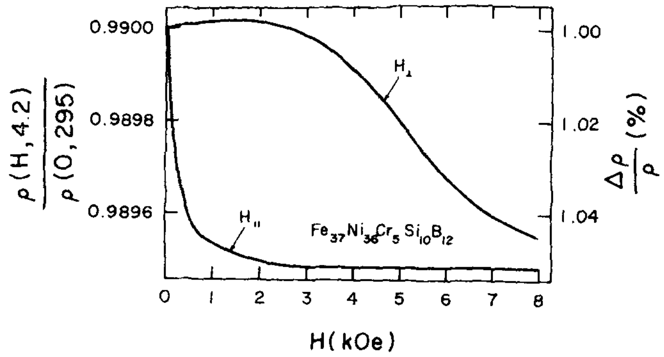

Fig. 4. Magnetoresistivity of Fe37 at 4.2 K. Fields are applied parallel and perpendicular to the plane of the foil, with current transverse to the field. Note the apparent effect of the demagnetizing factor in the soft ferromagnet.

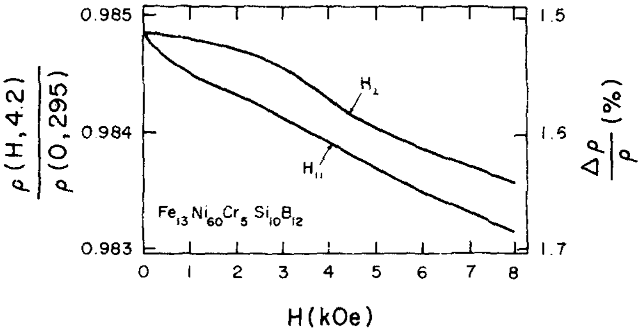

Fig. 5. Magnetoresistivity of Fe13 at 4.2 K. Fields are applied parallel and perpendicular to the plane of the foil, with current transverse to the field. Note absence of saturation as compared to Fig. 4.

In Fe13 the magnetoresistance is not typically ferromagnetic, as it does not saturate in the available magnetic fields when the field is parallel to the foil (Fig. 5). A large high field susceptibility has also been observed in this system [7], and has been attributed to Cr spin enhancement of the antiferromagnetic interaction. This leads to a p(H) distribution extending to more negative fields, and stronger Kondo

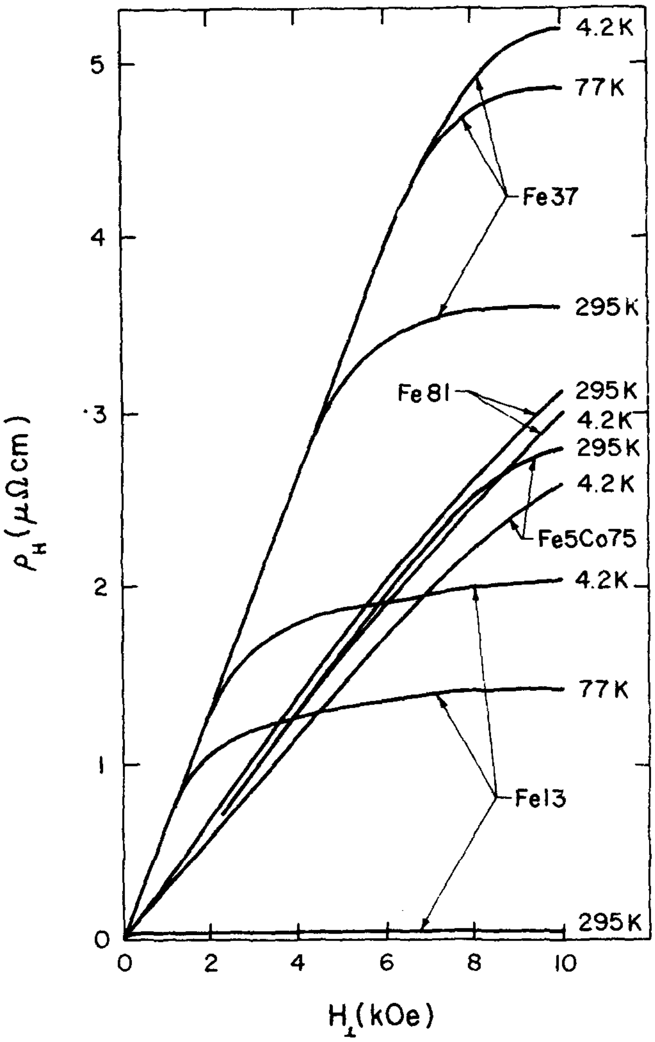

Fig. 6. Hall resistivity in several metallic glasses at several temperatures. Note that the two FeNiCr glasses have, within dimensional uncertainty a common low field behavior.

scattering. A positive slope in the tail of p(H) implies a large high-field susceptibility and a large negative slope in the magnetoresistnace at high fields [11]. This tendency is reduced in Fe37, which is a stronger ferromagnet with the peak of its p(H) farther from zero field. Thus, fewer spins participate in Kondo-type scattering. The positive magnetoresistance at very low fields is probably due to a small misalignment of the sample plane. [12,13].

The field dependence of the Hall resistivity ρ_H (Fig. 6) is given by [14],

$$\rho_H = R_o B + R_s 4\pi M \qquad (1)$$

where R_o and R_s are the ordinary and sponstaneous Hall coefficients and B is the magnetic induction perpendicular to the plane of the foil. For $H << 4\pi M_s$, demagnetization gives $H = 4\pi M$. Since $R_o << R_s$, then $\rho_H \sim R_s H$ and the spontaneous Hall coefficient can be found from the initial slope of the $\rho_H(H)$ curve. R_s can also be obtained from the extrapolation of the linear portion of the high-field $\rho_H(H)$ curve (Fig. 6). This extrapolation gives $R_s^* 4\pi M_s$, and from this, R_s^* is found using the known saturation magnetization M_s [7].

The values of R_s and R_s^* are listed in Table I. For both Fe13 and Fe37, R_s and R_s^* are in excellent agreement. Values of R_s are given for all four glasses and are similar to those of other amorphous materials [3]. Within dimension errors, R_s is the same for both (FeNi)CrSiB compositions and does not change with temperature below the Curie point. The shape of the $\rho_H(H)$ curves is, therefore, fixed by the saturation magnetization which is decreased at higher temperatures. This contrasts with Fe81 and Fe5Co75, where R_s is found to increase slightly at higher temperatures. R_s values for the (FeNi)CrSiB glasses are much higher than those of Fe81 and Fe5Co75.

The side jump of a hopping model [15] is proportional to the high field spontaneous Hall conductivity γ_{HS}, given by

$$\gamma_{HS} = 4\pi R_s M_s / \rho^2. \qquad (2)$$

We find $\gamma_{HS} \sim 10^2 \Omega^{-1} cm^{-1}$ (Table I), which is comparable to work by O'Handley [16], but lower than the values $\sim 10^3 \Omega^{-1} cm^{-1}$ for crystalline Fe, Co and Ni [17].

The ordinary Hall coefficient R_o can be found from the saturation portion of $\rho_H(H)$ (Fig. 6). Eq. (1) can be written in the form

$$\rho_H = R_o [H + 4\pi M(1-N)] + R_s 4\pi M \qquad (3)$$

H is perpendicular to the foil, so the demagnetizing factor $N \cong 1$. Then Eq. (3) becomes, $\rho_H = R_o H + R_s 4\pi M$. R_o can thus be determined from the high-field slope of the saturation $\rho_H(H)$ curve, the measured value of R_s and the high-field susceptibility $\chi = \partial M/\partial H$ from magnetic measurements [7]. Numbers were obtained only for the (FeNi)CrSiB glasses (Table I) because insufficient saturation was observed for the other glasses (Fig. 6). These values are larger than those of sputtered FeB films [18].

TABLE I

COMPOSITION	T (K)	ρ ($\mu\Omega$cm)	R_s	R_s^*	R_o	γ ($\Omega^{-1}cm^{-1}$)
			($10^{-4}\mu\Omega cmG^{-1}$)			
$Fe_5Co_{75}B_{15}Si_5$						
	295	156±8	3.3 ±0.4			118 ±20
	4.2	$.97\rho_{295}$	2.9 ±0.4			
$Fe_{13}Ni_{60}Cr_5Si_{10}B_{12}$						
	295	330±70				
	77	$.982\rho_{295}$	6.9 ±1.1			
	4.2	$.984\rho_{295}$	6.9 ±1.1	6.8 ±1.1	0.22 ±0.06	117 ±80
$Fe_{37}Ni_{36}Cr_5Si_{10}B_{12}$						
	295	210±90	6.9 ±2.3	6.8 ±2.3	0.10 ±0.05	
	77	$.964\rho_{295}$	6.9 ±2.3	6.3 ±1.3		122 ±85
	4.2	$.960\rho_{295}$	6.9 ±2.3			132 ±90
$Fe_{81}B_{13.5}Si_{3.5}C_2$						
	295	143±7	3.5 ±0.4			285 ±45
	4.2	$.97\rho_{295}$	3.2 ±0.4			

CONCLUSIONS

The resistivity, magnetoresistance and Hall effect have been measured over a range of temperatures. The resistivity minima observed in the (FeNi)CrSiB glasses appear to be magnetic in origin, as suggested by the field and temperature dependence of the magnetoresistance, Hall effect and high-field susceptibility. The spontaneous Hall coefficients are in good agreement with previous magnetization measurements. They are positive, and comparable to those of other amorphous materials, while the ordinary Hall coefficients are also positive.

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