Concentration dependence of the zero-temperature spontaneous resistive anisotropy in $(Pd_{1-x}Fe_x)_{95}Mn_5$

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Measurements of the low-temperature spontaneous resistive anisotropy (SRA) in ternary $(Pd_{1-x}Fe_x)_{95}Mn_5$ are presented; the SRA are shown to be consistent with a power-law behavior for this parameter, viz. SRA $\propto (c-c_0)/c_0$, and the exponent associated with the power law is estimated.

Several recent papers[1-3] have reported measurements of the magnetoresistive anisotropy in various Pd-based transition-metal systems. These data enabled estimates to be made of the so-called zero-temperature spontaneous resistive anisotropy (SRA) (actually measured at 1.5 K), the SRA being the difference between the longitudinal ($\rho_\parallel$) and transverse ($\rho_\perp$) magnetoresistance extrapolated to zero induction (B), viz.[4]

$$\frac{\Delta\rho(B)}{\rho_0} = \left[\frac{3\{\rho_\parallel(B)-\rho_\perp(B)\}}{\rho_\parallel(B)+2\rho_\perp(B)}\right]_{B\to 0;T=1.5\text{ K}}. \quad (1)$$

The concentration dependence of this ratio was then shown to follow a power-law behavior

$$\frac{\Delta\rho(B)}{\rho_0} \propto \left[\frac{c-c_0}{c_0}\right]^{\Delta} \quad (2)$$

suggesting that the SRA *might* display a zero-temperature percolation controlled behavior in the vicinity of a threshold concentration c_0. Such behavior is consistent with the established picture of Pd as an incipient ferromagnet in which exchange enhancement effects are important; this leads not only to the extensively studied giant moment phenomenon[5] in alloys such as *Pd*Fe, but also to the establishment of a ferromagnetic ground state produced[6,7] by a percolating backbone of such moments ferromagnetically coupled above a critical composition c_0. For *Pd*Fe, c_0 has recently[7,8] been estimated at $\simeq 10^{-2}$ at. % Fe, however for Ni in Pd no giant moment appears at the impurity site and the critical composition, $c_0 \simeq 2.25$ at. % Ni, is consequently larger.[9]

The appearance of an SRA in *any* system relies on the presence of spin-orbit coupling,[10] and hence an orbital component in the total moment of the system. Furthermore, while both localized[11] and itinerant[12] models have been utilized in the interpretation of SRA data, the former approach affords a more direct means of both understanding and calculating such effects, as recent papers demonstrate.[13] Indeed, localized models alone currently appear capable of providing a quantitative estimate for the "exponent" Δ in Eq. (2), yielding[13] $\Delta = 1.2$. This model value is close to that measured[3] for Fe in Pd ($\Delta = 1.0 \pm 0.05$) but is well below the value reported[2] for Ni in the same host ($\Delta = 9/4 \pm 0.1$), a somewhat surprising result since Ni is known to carry an orbital moment[14] in this matrix (suggesting the applicability of a localized approach) whereas Fe does not[14] (the anisotropy here results from spin-orbit coupling in the impurity induced, exchange split Pd *d bands*[3]).

In the course of investigating the electric[15] and magnetic[16] properties of ternary $(Pd_{1-x}Fe_x)_{95}Mn_5$, a potential reentrant system,[17,18] the anisotropy of its magnetoresistance was also measured. Despite various complications (discussed below), these data contribute to the question of the possible universality of the index Δ.

Samples with nominal x values of 0.35, 1.6, 1.8, 2.0, and 2.2 at. % were prepared individually following a series of melting and remelting, cold-rolling, and annealing steps.[15] Magnetoresistance measurements were made using a low-frequency ac technique[15] on samples with typical dimensions $(35\times 2\times 0.1)$ mm^3 at 4.2 and 1.5 K in applied fields up to 1 T in both the longitudinal and transverse configurations, and in fields up to 8.5 T in the longitudinal geometry alone.

Figure 1 reproduces the magnetoresistance at 1.5 K measured in both orientations for applied fields $\mu_0 H_a$ up to 1 T on the 1.8 at. % Fe sample, while Fig. 2 displays data from the same sample in longitudinal fields alone up to 8.5 T. These figures are typical of the data obtained on all the specimens studied, a summary of which appears in Table I. The principal feature evident in both figures is the strong negative component in the magnetoresistance in either orientation, a feature that demonstrates unambi-

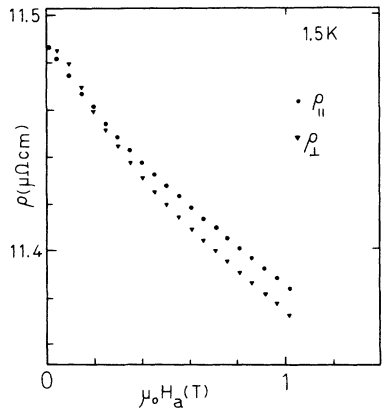

FIG. 1. The longitudinal ($\parallel$) and transverse ($\perp$) magnetoresistance of the $x = 1.8$ at. % Fe sample at 1.5 K in applied fields ($\mu_0 H_a$) up to 1 T.

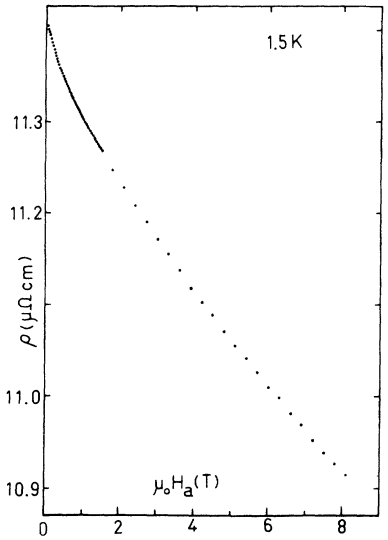

FIG. 2. The longitudinal magnetoresistance of the $x=1.8$ at. % Fe specimen at 1.5 K in applied fields ($\mu_0 H_a$) up to 8 T.

guously the persistence of substantial spin noncollinearity at temperatures well below the ferromagnetic ordering temperature[16] ($T_c \simeq 42$ K). This behavior is in marked contrast to that exhibited by the binary Pd_xFe_{1-x} system,[3] where the magnetoresistance in either orientation displays a weak dependence on fields above $\mu_0 H_a \simeq 0.5$ T, thus enabling the SRA to be estimated—using the extrapolation implicit in Eq. (1)—with reasonable accuracy. However, as recently pointed out,[15] despite the complications associated with the failure of either $\rho_\parallel$ or $\rho_\perp$ to reach saturation in the ternary system, the *resistive anisotropy* can, nevertheless, be estimated, as the following argument shows.

In Fig. 3(a) the data contained in Fig. 1 are replotted against the induction B, while Fig. 3(b) reproduces the magnetoresistive anisotropy $\Delta\rho(B)$, where

$$\Delta\rho(B)=\rho_\parallel(B)-\rho_\perp(B) \tag{3}$$

while the induction B is given by

$$B=\mu_0(H_a+M)-NM\ , \tag{4}$$

in which M is the magnetization and N the appropriate demagnetization factor. There exist compelling arguments[4] for basing the extrapolation implicit in Eq. (1) on B, rather than H_a or H_i (the internal field) (at least at low temperatures, where de Haas-van Alphen oscillations in

TABLE I. A summary of SRA measurements on (*Pd*Fe)Mn.

			1.5 K		4.2 K	
Fe conc (at. %)	ρ_0^a ($\mu\Omega$ cm)	T_c (K)	$\Delta\rho$ ($n\Omega$ cm)	SRA (%)	$\Delta\rho$ ($n\Omega$ cm)	SRA (%)
2.2	12.40	48	31±1	0.25	31±1	0.25
2.0	11.89	45	29±1	0.24	29±1	0.24
1.8	11.49	42	25±1	0.22	25±1	0.22
1.6	11.12	38	17±1.5	0.15	16.5±1.5	0.15
0.35	8.33	9.3	3.3±0.5	0.04(0)	3.0±0.5	0.03(5)

[a]Subject to typically ±1% uncertainty in absolute value due to shape factor errors; this does not influence the SRA appreciably.

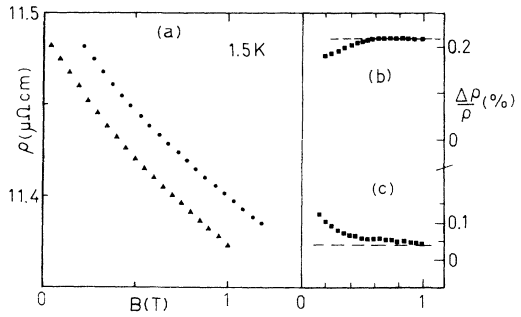

FIG. 3. (a) The data of Fig. 1 replotted against the estimated induction B (in T) as explained in the text. (b) The anisotropy ratio $\Delta\rho/\rho_0$ (in %)—with $\Delta\rho$ given by Eq. (3)—plotted against B (in T) for the $x=1.8$ at. % sample at 1.5 K. (c) As in (b), for the $x=0.35$ at. % Fe specimen.

ferromagnets are periodic in B^{-1}), and it is the shift induced by replotting the data in Fig. 1 against B that plays the principal role in subsequent estimation of the SRA in this ternary system (as a closer comparison between Figs. 1 and 3 confirms[19]). For this reason the evaluation of the induction using Eq. (4) was carried out carefully. As briefly discussed previously,[15] B was calculated directly using previously published magnetization—field data[20] (or scaling it, where necessary, for samples of slightly different composition) together with the demagnetization factors ($N_\parallel$ or $N_\perp$) appropriate for the experimental geometry. These latter factors were calculated using the averaged, measured dimensions of each specimen in an evaluation of the corresponding elliptic integral.[21] It is therefore important to emphasize that the geometry/dimensions were specifically designed such that, while $N_\perp \simeq \mu_0$ (so that there is *no change* between the data acquired in the perpendicular orientation in Figs. 1 and 3), $N_\parallel \simeq 5\times10^{-4}\mu_0$ so that, typically, $M(\mu_0-N_\parallel)\simeq\mu_0 M\simeq 0.2$ T; the latter induces a substantial shift between $\rho_\parallel$ in Figs. 1 and 3, this shift (as mentioned above) playing a central role in the evaluation of the SRA. It is clearly important therefore to examine the reliability of these estimates; *they are determined by that of the published magnetization data* (an accurately measurable property) *not on the detailed values adopted for the demagnetization factors* (due to the particular sample geometry selected).

Having made this point, the behavior evident in Fig. 3 which we wish to exploit is that the resistive *anisotropy* ratio $\Delta\rho/\rho_0$ appears to saturate near $B\simeq 0.4$ T despite the individual dependence of $\rho_\parallel$ and $\rho_\perp$ on H_a (or B); the SRA can thus be estimated using the extrapolation shown. The behavior summarized in Fig. 3(b) is typical of all samples studied containing more than 1 at. % Fe; that shown in Fig. 3(c) for the $x=0.35$ at. % Fe sample is slightly less conclusive in that the ratio $\Delta\rho(B)/\rho_0$ displays a weak dependence on B above ~ 0.5 T leading to a larger uncertainty in the SRA (as shown in Table I). We suggest that the failure of $\Delta\rho(B)$ to saturate in this one sample results from the marked reduction in the ratio of the measuring temperature (~ 1.5 K) to its ordering temperature ($T_c \simeq 9$ K), a suggestion that is supported by the further reduction in the estimate for its SRA at the

higher measuring temperature of 4.2 K (a reduction which is not so marked in the other samples where T_c is considerably higher).

Figure 4 summarizes the SRA data so obtained in the form suggested by Eq. (2), i.e., a plot of this ratio against the reduced composition $(c-c_0)/c_0$ on a double logarithmic scale. There does not exist currently an estimate for the critical composition c_0 based on a detailed analysis of the properties of this ternary system; consequently we have *estimated* c_0 by taking the most recent[7,22] value for this composition obtained from a detailed compilation of binary *Pd*Fe alloys, and scaling it by the averaged ratio of T_c in the ternary system (Table I) to that in the corresponding binary *Pd*Fe system,[7] we thus obtain $c_0 \simeq 0.015$ at. % Fe. The solid line drawn in this figure corresponds to the power-law relationship of Eq. (2) with $\Delta \sim 1$; lowering c_0 increases the estimate for Δ and vice versa. Despite the limitations imposed on these data by the uncertainty in c_0 and the difficulty of estimating SRA value at low Fe concentration, they are nevertheless consistent not only with a power-law dependence of the SRA near the critical composition but with an exponent Δ which is estimated to be close to that reported[7] for binary *Pd*Fe ($\Delta = 1.00 \pm 0.05$). This latter result is expected since neither Fe or Mn separately carry an orbital moment in this matrix,[14] and (*Pd*Fe)Mn is a comparably soft ferromagnet[18] to either [3] *Pd*Fe or[22] *Pd*Mn. The expectation is therefore that this exponent might be in the same universality class, and the experimental data are consistent with this expectation.

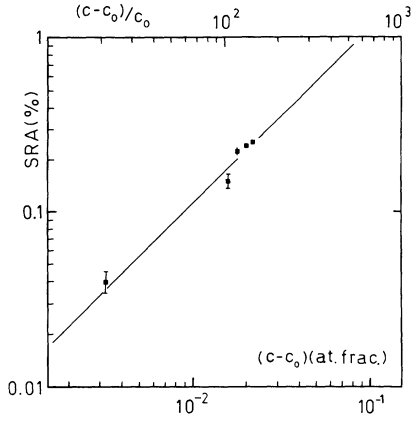

FIG. 4. The SRA (in %)—estimated from extrapolation similar to that shown in Figs. 3(b) and 3(c)—plotted against the atomic fraction $(c-c_0)$ (lower scale) and the reduced composition $(c-c_0)/c_0$ (upper scale) for the samples investigated. The line drawn has a slope of approximately unity.

Other candidate systems which exhibit possible zero-temperature percolation controlled transitions, and in which both the critical composition c_0 and the SRA are better defined are currently being sought to further elucidate this problem.

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