Magnetic scattering in the amorphous ferromagnets $Fe_{80}B_{20-x}Si_x$ $(0 \leq x \leq 12)$

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The electrical resistivity in the amorphous ferromagnets $Fe_{80}B_{20-x}Si_x$ $(0 \leq x \leq 12)$ has been measured in the temperature range 8–300 K. We find from a detailed quantitative analysis that over and above a dominant structural contribution there exists in such alloys a significant magnetic contribution proportional to $T^{3/2}$ for $T \ll \Theta_D$ (Debye temperature). No definite conclusion could be reached about the temperature dependence ($T^{3/2}$ or T^2) of the magnetic contribution at higher temperatures, viz., $T \geq \Theta_D$. Magnetoresistance data show that the temperature dependence of the resistivity is not affected in the presence of external magnetic fields. However, the coefficient of the magnetic term shows a small decrease with increasing field at low temperatures but remains constant at high temperatures.

I. INTRODUCTION

The electrical resistivity in metallic glasses is a very important subject as the noncrystallinity of the materials affects the electronic transport properties. In recent years the study of these properties has been a subject of widespread interest. In particular, the electrical resistivity provides a very sensitive probe with which one can try to understand various scattering processes that occur in a given material.

Earlier[1] we had measured the electrical resistivity (ρ), magnetoresistance, and Hall effect in $Fe_{100-x}B_x$ $(13 \leq x \leq 26)$ binary metallic glasses. The temperature coefficient of the resistivity and the concentration dependence of the absolute value of ρ were explained in terms of Ziman's theory[2] of liquid metals. An attempt was also made to find the magnetic contribution to the resistivity between 20 and 100 K. Due to the relatively poor resolution of the data, no definite conclusion could be drawn. However, in magnetic materials, over and above the scattering of electrons by structural disorders and lattice vibrations, there must be some evidence of magnetic scattering. Theoretically, according to Richter *et al.*,[3] the leading term in the magnetic resistivity of amorphous ferromagnets is a $T^{3/2}$ one followed by a higher-order T^2 term. An excellent review has been made recently by Vasvari.[4] Experiments which claim to have observed a magnetic contribution to ρ fall under two categories.

(a) A magnetic contribution proportional to T^2. Bergmann and Marquardt[5] had concluded the existence of a T^2-dependent magnetic term on the basis of straight-line plots of ρ versus T^2 in binary Ni-Au, Co-Au, and Fe-Au amorphous ferromagnets. This method is not conclusive since the structure factor term (see Sec. II), which should be included in the total ρ, also has a T^2 dependence. Thummes *et al.*[6] found qualitative evidence of a T^2 magnetic term in $Ni_{80-x}Fe_xSi_8B_{12}$ $(2.4 \leq x \leq 16)$ metallic glasses. They also found an unusually low Debye temperature ($\Theta_D < 100$ K). Kaul *et al.*[7] have established, from a detailed quantitative analysis of the resistivity data of amorphous $Fe_{80}B_{20-x}C_x$ ($x = 0$, 2, 4, and 10) alloys, that besides a dominant structural contribution, there exists in such alloys a significant magnetic contribution to ρ proportional to T^2.

(b) A magnetic contribution proportional to $T^{3/2}$. In Fe-Ni-P-B glasses, Babic *et al.*[8] obtained a $T^{3/2}$ term from linear total ρ versus $T^{3/2}$ plots for $T < T_c/3$. No structural contribution was considered. Kettler and Rosenberg[9] found a $T^{3/2}$ magnetic term in Ni-based $Ni_{80-x}Fe_xB_{16}Si_4$ ($x = 0$–19) and $Ni_{77-x}Fe_xB_{13}Si_{10}$ ($x = 0$–15.4) by subtracting at each temperature the total resistivity of the nickel parent alloy ($x = 0$) from those of the above alloys. This was done on the assumption that the magnetic contribution to the total ρ was due to the added iron. They also found that the magnetic term decreased with increasing Fe content.

Thus, it is quite clear that a controversy still exists in deciding the relative weight of the $T^{3/2}$ and T^2 magnetic contributions to the total resistivity in ferromagnetic metallic glasses. It should be emphasized here that such distinctions cannot be made by merely observing ρ versus $T^{3/2}$ or ρ versus T^2 curves as straight lines. A quantitative criterion, e.g., the value of χ^2 in different fits, is needed as it has been used only by Kaul *et al.*[7]

We have taken high-resolution electrical resistivity data in seven $Fe_{80}B_{20-x}Si_x$ $(0 \leq x \leq 12)$ ferromagnetic metallic glasses between 8 and 300 K with the following aim.

(a) To determine whether there is any magnetic contribution at all in these materials.

(b) If there is, does it occur through a $T^{3/2}$ term which is theoretically[3] the leading term in amorphous materials or through a T^2 term as found quantitatively by Kaul *et al.*[7] in a similar system?

The magnetoresistance, both transverse and longitudinal, was also measured for $x = 0$, 6, and 12 between 10 and 300 K using magnetic fields up to 16.5 kOe in order to study its effect on magnetic scattering.

II. THEORY

Customarily, $\rho(T)$ in amorphous materials is explained in terms of the Ziman theory of liquid metals in which the temperature dependence of resistivity comes through

the structure factor. The asymptotic forms are given by

$$r_s(T)=\rho_s(T)/\rho(0\,^\circ\mathrm{C})$$
$$=\begin{cases}a_0+b_2T^2 & \text{for } T\ll\Theta_D\ , \quad (1)\\ a_0'+c_1'T & \text{for } T\geq\Theta_D\ . \quad (2)\end{cases}$$

where $\rho(0\,^\circ\mathrm{C})$, the resistivity at 273 K, is used for normalizing the data and Θ_D is the Debye temperature.

Richter *et al.*[3] have calculated the spin-disorder resistivity of amorphous ferromagnets by using the force-force correlation function method up to second order in the *s-d* exchange constant. They found, at low temperatures ($T\ll T_C$ where T_C is the Curie temperature) and zero external field that

$$r_m(T)=\rho_m(T)/\rho(0\,^\circ\mathrm{C})=\rho_0+aT^{3/2}+bT^2\ , \quad (3)$$

neglecting a small correction to the electron-magnon coherent scattering due to the influence of topological disorder. ρ_0 is proportional to the residual spin-disorder resistivity. The $T^{3/2}$ dependence comes from (a) the elastic scattering of electrons by a temperature-dependent, randomly distributed local magnetic moment which decreases with increasing temperature and (b) incoherent electron-magnon momentum nonconserving scattering which increases with increasing temperature. The latter term overcompensates the former and, as a result, the net $T^{3/2}$ term is positive. However, this term vanishes for the crystalline case. The T^2 term comes from the coherent electron-magnon scattering, as in the crystalline case. For low T ($\ll\Theta_D$), the contribution should be predominantly from the $T^{3/2}$ term whereas, for moderate T ($\simeq\Theta_D$), it should be from the T^2 term. In both cases it is assumed that $T\ll T_C$.

If the magnetic contribution occurs through the T^2 term, then assuming Matthiessen's rule,

$$\rho(T)=\rho_s(T)+\rho_m(T)\ ,$$

the total normalized resistivity becomes [by adding Eqs. (1) and (3), except for the $T^{3/2}$ term]

$$r(T)=(a_0+\rho_0)+(b_2+b)T^2$$
$$=\alpha_0+\alpha_2T^2,\quad T\ll\Theta_D\ . \quad (4a)$$

If the magnetic contribution occurs through the $T^{3/2}$ term, then [by adding Eqs. (1) and (3), except for the T^2 magnetic term]

$$r(T)=(a_0+\rho_0)+b_2T^2+aT^{3/2}$$
$$=\alpha_0+\alpha_2T^2+\alpha_{3/2}T^{3/2},\quad T\ll\Theta_D\ . \quad (4b)$$

Similarly, by adding Eqs. (2) and (3), one gets

$$r(T)=(a_0'+\rho_0)+c_1'T+bT^2$$
$$=\alpha_0'+\alpha_1'T+\alpha_2'T^2,\quad T\geq\Theta_D \quad (5a)$$

and

$$r(T)=(a_0'+\rho_0)+c_1'T+aT^{3/2}$$
$$=\alpha_0'+\alpha_1'T+\alpha_{3/2}'T^{3/2},\quad T\geq\Theta_D\ . \quad (5b)$$

If the magnetic contribution is not considered at all, then

$$r(T)=\begin{cases}\alpha_0+\alpha_2T^2, & T\ll\Theta_D\ , \quad (6a)\\ \alpha_0'+\alpha_1'T, & T\geq\Theta_D. \quad (6b)\end{cases}$$

III. EXPERIMENT

Amorphous $Fe_{80}B_{20-x}Si_x$ ($x=0$, 1, 2, 4, 6, 8, and 12) alloy ribbons were provided to us by Luborsky of the General Electric Company. These amorphous ribbons were prepared by melt quenching onto the surface of a rotating wheel. Electrical resistivity measurements were made from 8 to 300 K using a four-probe dc method. The electrical leads to the sample were soldered with nonsuperconducting solder (eutectic Cd-Zn). Temperatures down to 8 K were achieved by using a closed-cycle helium refrigerator (Cryogenic Technology Inc.). The resistance R was directly measured using a Datron 1071 Autocal digital multimeter with a current of 10 mA. The sample temperature was monitored by a silicon diode and controlled by a Lakeshore DRC-82C temperature controller having a temperature stability of about 0.05 K. The accuracy of $\Delta R/R$ was better than 1 part in 10^5.

For samples with $x=0$, 6, and 12, magnetoresistance was also measured in both orientations (current density $\mathbf{J}\|\mathbf{M}$ and $\mathbf{J}\perp\mathbf{M}$, where $\mathbf{M}$ is the magnetization) as a function of fields up to 16.5 kOe using a 15-in. Varian V-3800 electromagnet and at several constant temperatures between 10 and 300 K. The temperature was then controlled by a carbon-glass thermometer which showed very little magnetoresistance effects. Measurements were also taken at about 110 temperatures between 10 and 300 K at constant magnetic fields of 2, 7, and 14 kOe. The sample current was increased to 100 mA, as a result of which the accuracy of $\Delta R/R$ was about 1 part in 10^6.

IV. RESULTS AND DISCUSSION

A. Resistivity

The temperature dependence of the normalized resistivity $r(T)=\rho(T)/\rho(0\,^\circ\mathrm{C})$ in the temperature range 8–300 K for an amorphous $Fe_{80}B_{20-x}Si_x$ ($x=0$, 1, 2, 4, 6, 8, and 12) series is shown in Figs. 1 and 2. In this temperature range these glasses are ferromagnetic with T_C more or less constant between 645 and 680 K. The values of ρ at different temperatures have been normalized to the resistivity value at 273 K because there is a large error in the measurements of the ribbon thickness and width, resulting in a large inaccuracy in the absolute values of ρ. The ρ versus x plot does not show any specific trend. Its room-temperature value is $127\pm10\ \mu\Omega\,\mathrm{cm}$ for the whole series. Figures 1 and 2 show that ρ changes by 3–4% from 8 to 300 K. The temperature at which they show a minimum varies from 11 to 16 K.

The dispersion in the data is rather low and the number of data points are sufficiently large for us to draw meaningful conclusions from their fits to Eqs. (4)–(6). We have used a least-squares-fit program in Pascal on the

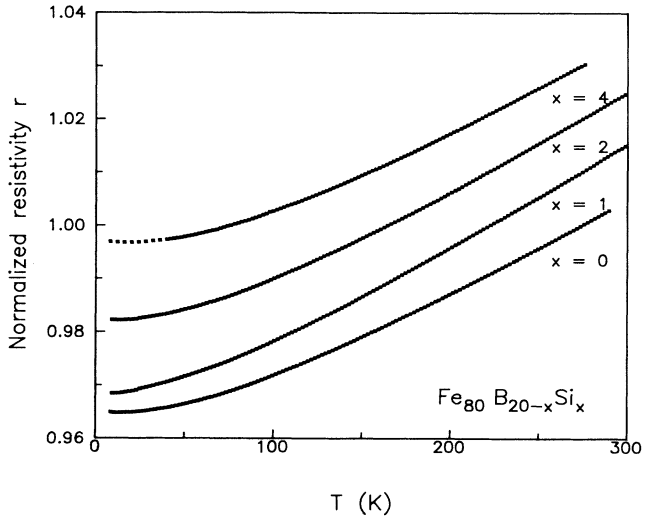

FIG. 1. Temperature dependence of the normalized resistivity r for amorphous $Fe_{80}B_{20-x}Si_x$ ($x=0$, 1, 2, and 4) alloys. Each curve is displaced along r axis by 0.01 with respect to the one below it.

IBM PC microcomputer. Table I shows the fits between 35 and 85 K to Eqs. (4) for all the samples with two terms [Eq. (4a)] and three terms [Eq. (4b)]. One should note that $r(T)$ in Eqs. (4)–(6) is of the order of 1, thus a χ^2 of the order of 10^{-10} represents a very good fit since the accuracy of $R(T)$ itself is only a few parts in 10^6. Here we have defined χ^2 as

$$\chi^2=\sum_{l=1}^{N}[r(T)_l(\text{measured})-r(T)_l(\text{calculated})]^2/N \ ,$$

where N is the number of data points. From the values of χ^2 it is obvious that the inclusion of the $T^{3/2}$ term invariably improves the fit very significantly and, in some cases, even by more than an order of magnitude. The fact that

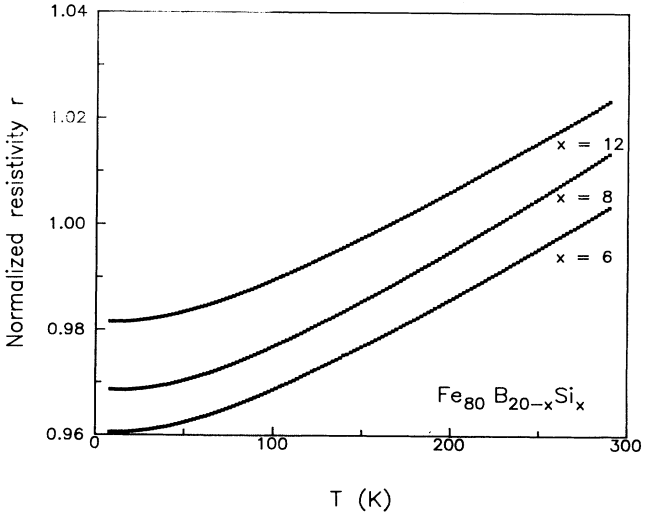

FIG. 2. Same as in Fig. 1 for $x=6$, 8, and 12 alloys.

there is another term present over and above the T^2 (here $T^{3/2}$) term is further demonstrated in Fig. 3. It shows the deviations of individual data points from the best-fitted curve using (a) Eq. (4a) and (b) Eq. (4b) for samples with $x=0$, 1, 6, and 12. It is clear that, in case of (a), the deviation is large and systematic whereas, in case of (b), it is small and random (i.e., intersecting the zero deviation line more frequently).

Fitting the data between 200 and 300 K to Eqs. (5) and (6b), significant improvement in the value of χ^2 is achieved with the inclusion of either T^2 [Eq. (5a)] or $T^{3/2}$ [Eq. (5b)] terms over the linear term only [Eq. (6b)]. However, there is nothing much to choose between the two alternatives from the χ^2 values. Thus, it is very difficult to conclude whether it is a T^2 or a $T^{3/2}$ term that has to be added to the linear electron-phonon term at high temperatures. We have also tried to fit the data between 200 and 300 K with both terms together, i.e., T^2 and $T^{3/2}$ terms in addition to the linear one. We find that the coefficient of one of the terms (T^2 or $T^{3/2}$) becomes negative and, hence, unacceptable in the present context. It should be pointed out that any quantitative data analysis involving more terms (here four) demands more resolution of the data.

In order to establish a magnetic contribution (be it T^2 or $T^{3/2}$) on a firmer basis, in Fig. 4, $dr(T)/dT$ is plotted against temperature for samples with $x=0$, 2, 6, and 8. For the $35<T<85$ K region, the derivative varies slower than T, which definitely implies that over and above a T^2 term there is a term which varies faster than T and slower than T^2. The 85–200 K region is one of a transition between two regions where different mechanisms come into play and, hence, has been left out in this quantitative analysis. The derivative curves above 200 K are not horizontal. If there were only a linear term in $r(T)$ (i.e., no magnetic contribution), the derivative would have been a constant. An additional T^2 term will give a derivative which is linear in T. A slight curvature observed here might indicate the presence of a $T^{3/2}$ term instead of a T^2 one.

Using Eqs. (6), i.e., without considering any magnetic contribution, one gets

$$\Theta_D^1 \simeq \frac{\pi^2}{6}\frac{\alpha_1'}{\alpha_2} \ . \tag{7}$$

If we consider Eqs. (4a) and (5a), i.e., the magnetic term is T^2 in both ranges of temperature, Θ_D will be given by

$$\Theta_D^2 \simeq \frac{\pi^2}{6}\frac{\alpha_1'}{\alpha_2-\alpha_2'} \ . \tag{8}$$

If we consider that the magnetic term is $T^{3/2}$ in both ranges of temperature, then the value of Θ_D can be found, with use of Eqs. (4b) and (5b), to be

$$\Theta_D^3 \simeq \frac{\pi^2}{6}\frac{\alpha_1'}{\alpha_2} \ . \tag{9}$$

The values of Θ_D, obtained from Eqs. (7)–(9), are given in Table I. We have intentionally not included the values

of α_0 and α_0' in the table since they are subsequently not used. However, the values are $\simeq 0.96$.

It is also observed that the coefficients are rather sensitive to the temperature range of the various fits. Hence, their composition dependence, as well as that of Θ_D, which solely depends on these coefficients, could not be determined from the present work. Since the transition-metal (Fe) content is the same in all the alloys, a strong composition dependence is also not expected. However, the coefficients of the magnetic terms [viz., $\alpha_{3/2}$, $\alpha_{3/2}'$, and α_2' of Eqs. (4b), (5b), and (5a), respectively] depend on various parameters, such as the unit-cell volume, the spin of the local magnetic moment, spin-wave stiffness constant, structure factor, Fermi momentum, etc.[3] The different kinds of composition dependence of all these factors put together may be partly responsible for the random variation of these coefficients. More reproducible and higher-resolution data are necessary to quantitatively find the effect of composition on these coefficients. The present work only establishes their values within a factor of 2. Thus, we have included their averages and standard deviations at the end of Table I.

If T^2 is taken as the magnetic term, then the average values of the coefficients $10^7\alpha_2$, $10^4\alpha_1'$, and $10^7\alpha_2'$ obtained by Kaul *et al.*[7] in $Fe_{80}B_{20-x}C_x$ (5.5 ± 0.7, 1.0 ± 0.1, and 0.7 ± 0.3, respectively) agree well with those found by us

TABLE I. Composition, coefficients for fits to Eq. (4) and resulting χ^2, coefficients for fits to Eqs. (5) and (6b) and resulting χ^2 and values of Θ_D obtained from Eqs. (7)–(9) in $Fe_{80}B_{20-x}Si_x$ ($0 \le x \le 12$) amorphous ferromagnets.

	Range of fit: 35–85 K			Range of fit: 200–300 K				
x (at. %)	$10^7\alpha_2$ (K^{-2})	$10^6\alpha_{3/2}$ ($K^{-3/2}$)	χ^2 (10^{-10})	$10^4\alpha_1'$ (K^{-1})	$10^7\alpha_2'$ (K^{-2})	$10^6\alpha_{3/2}'$ ($K^{-3/2}$)	χ^2 (10^{-10})	Θ_D (K)
				1.8			41.9	386[1]
	7.5		3.9					
0				1.3	1.1		1.8	319[2]
	5.6	2.0	0.9	0.7		4.4	1.9	217[3]
				1.9			69.9	353
	9.0		42.4					
1[a]				1.4	1.1		8.3	288
	2.1	7.8	1.6	0.9		4.4	8.7	694[b]
				1.9			28.3	385
	8.1		9.2					
2				1.6	0.7		4.3	346
	5.2	3.0	2.1	1.2		2.8	4.2	381
				1.7			15.6	435
	6.6		10.0					
4[a]				1.4	0.7		5.1	396
	5.8	0.9	9.4	1.1		3.0	5.0	303
				2.0			17.1	367
	8.7		7.2					
6				1.7	0.5		7.0	339
	5.9	2.9	0.5	1.4		2.2	7.0	402
				2.1			48.3	376
	9.0		2.7					
8				1.5	1.1		2.4	315
	7.7	1.4	1.2	1.0		4.7	2.4	206
				1.9			33.6	364
	8.6		15.0					
12				1.5	0.7		13.6	323
	4.5	4.2	0.9	1.2		3.1	13.8	432
Ave	8.2 ± 0.9			1.9 ± 0.1	0.8 ± 0.3			381 ± 27
rage				1.5 ± 0.1				329 ± 39
	5.8 ± 1.1	2.4 ± 1.2		1.1 ± 0.2		3.4 ± 1.0		324 ± 97

[a]For $x = 1$ and 4, the range of fit at low temperatures 45–95 K.
[b]The numbers in this row are not used for calculating the averages.

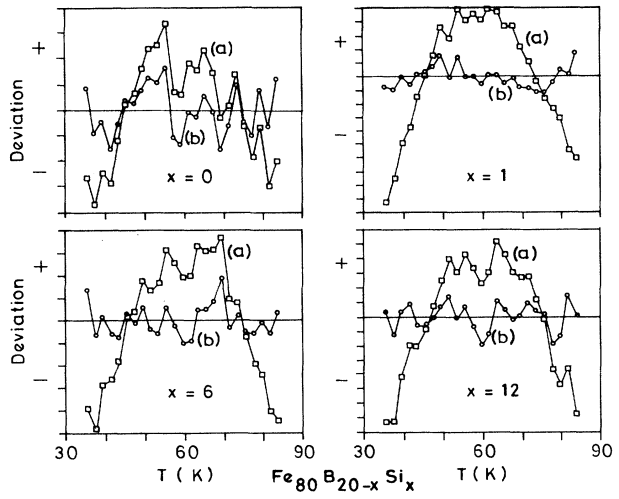

FIG. 3. Deviation vs temperature for $x=0$, 1, 6, and 12 alloys. (a) denotes deviations of data points from fits to Eq. (4a) and (b) from fits to Eq. (4b).

(Table I), namely, 8.2±0.9, 1.5±0.1, and 0.8±0.3, respectively. The resulting Θ_D values 330±40 K are realistic and consistent with the literature value for the $x=0$ alloy.[10] Nevertheless, we also find equally good fits if $T^{3/2}$ is taken as the magnetic term. The values of the coefficients $\alpha_{3/2}$ and $\alpha'_{3/2}$ are nearly equal to each other ($=3\times10^{-6}$ $K^{-3/2}$) implying that the same $T^{3/2}$ term could exist over the entire temperature range. Their values have the same order of magnitude as that in a different amorphous material[3] Co_4P where the value is 16×10^{-6} $K^{-3/2}$. However, Θ_D values then become widely different from one another with an average of 324±97 K.

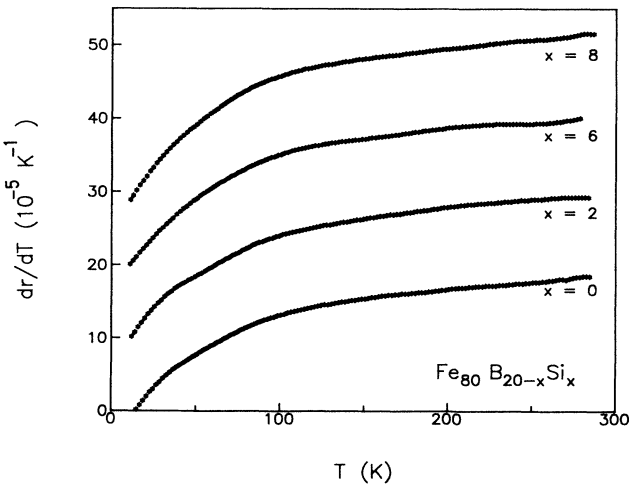

FIG. 4. Temperature derivative of the normalized resistivity dr/dT (10^{-5} K^{-1}) as a function of temperature for $x=0$, 2, 6, and 8 alloys. Each curve is displaced along dr/dT axis by 10^{-4} with respect to the one below it.

One possible explanation for the apparent discrepancy in Θ_D could be the following: Eq. (3) is valid for $T \ll T_c$. The lower temperature range for fitting our data to Eqs. (4a) and (4b) is 35–85 K for which $T \leq 0.13T_C$. Thus, our observation of the $T^{3/2}$ term dominating over the T^2 term at lower temperatures seems quite reasonable. But the higher range for fitting the data to Eqs. (5a) and (5b) is 200–300 K ($T \leq 0.45T_C$). The latter range may not satisfy the criterion $T \ll T_C$. As a result, the use of Eq. (3) as predicting the magnetic contribution in this range may not be correct. Thus, the coefficient of the linear term (electron-phonon scattering) α'_1 will be erroneous and will affect the value of Θ_D adversely [see Eqs. (8) and (9)]. However, if that was the case, the set of more reasonable Θ_D, obtained from Eq. (8), would have to be taken as fortuitous. Thus, we conclude that the magnetic contribution to the total resistivity is indeed through the $T^{3/2}$ term at least for $T \ll \Theta_D$. Also, the temperature range $T \geq \Theta_D$ is likely to be outside the domain of Eq. (3) in predicting the magnetic term.

B. Magnetoresistance

The longitudinal ($\mathbf{J}\|\mathbf{M}$) and transverse ($\mathbf{J}\perp\mathbf{M}$) magnetoresistances for a polycrystalline material are given by[1,11] $\Delta\rho_\|/\rho=(\rho_\|-\rho)/\rho$ and $\Delta\rho_\perp/\rho=(\rho_\perp-\rho)/\rho$, respectively, where $\rho_\|$ and $\rho_\perp$ are the resistivities in longitudinal and transverse magnetic fields and ρ is the resistivity in zero external field H_{ext}. Typical magnetoresistance curves are shown in Fig. 5 for the sample with Si concentration $x=6$ at several temperatures. We find that these amorphous materials behave very much the same way as their crystalline counterparts, namely, at low fields the longitudinal magnetoresistance is positive while the transverse one is negative. At higher fields, both of them decrease very slowly but linearly with field. This behavior must be contrasted with the Lorentz force magnetoresistance (positive for both $\|$ and $\perp$ orientations with $\rho_\perp>\rho_\|$) which varies as H^2 and is sizable only for pure metals or dilute alloys at low temperatures and high mag-

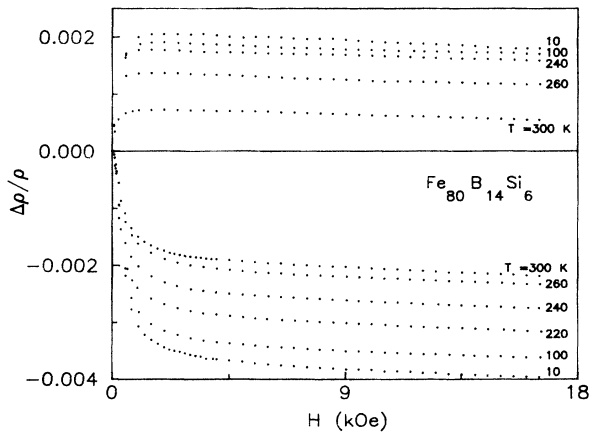

FIG. 5. Magnetoresistance ($\Delta\rho/\rho$) vs external magnetic field at several constant temperatures for both longitudinal ($\mathbf{J}\|\mathbf{M}$) and transverse ($\mathbf{J}\perp\mathbf{M}$) orientations for $x=6$.

netic fields. The ferromagnetic anisotropy of the resistivity (FAR) is defined by a quantity $(\rho_{\parallel_s}-\rho_{\perp_s})/\rho_0$, where ρ_0 is the resistivity for $H_{int}=0$. $\rho_{\parallel_s}$ and $\rho_{\perp_s}$ are the resistivities extrapolated to $H_{\rm int}=0$ ($H_{\rm int}=H_{\rm ext}-H_{\rm demag}$). For our samples the demagnetization field $H_{\rm demag}\simeq 1$ Oe for $\rho_{\parallel}$ and $\simeq 400$ Oe for $\rho_{\perp}$.

The calculated values of the FAR are plotted against temperature for $x=0$, 6, and 12 in Fig. 6(a). The FAR is found to be positive and its value decreases with increasing temperature but at low temperatures (<200 K) the decrease is very slow. This is also clear from Fig. 5 where we find that the curves for $T\geq 220$ K are well separated from each other, resulting in a faster decrease of the FAR with temperature. The slow decrease of FAR at low temperatures is due to the fact that, in this range of temperature, $T<T_C/3$, where the typical Curie temperature is 660 K. The ferromagnetic anisotropy of the resistivity has its origin in the spin-orbit interaction present in a ferromagnet. It has been shown by Smit[12] that $\rho_{\parallel}>\rho_{\perp}$, which results in a positive FAR. This anisotropy is smaller for lattice vibrations justifying the general shape of Fig. 6(a). Since T_C and the saturation magnetization[13] are found to vary slowly with the Si concentration x, one would expect the FAR to be weakly dependent on x. However, we find that although the FAR values for $x=6$ and 12 are nearly the same, they are 30% lower than that for $x=0$. We have also plotted the spontaneous linear magnetostriction coefficient[14] λ_s versus T for $x=0$ in Fig. 6(a). It roughly follows the FAR versus T graph since the origin of the two effects lies in the spin-orbit interaction.

In isotropic crystalline ferromagnets,[15] the ratio $(\rho_{\parallel}-\rho)/(\rho_{\perp}-\rho)\simeq -2$. Here, for all three samples, we find that this ratio is $\simeq -0.5$. This implies that the domain magnetization is not randomly oriented in these amorphous ribbons. Using the relation,[1]

$$\tan^2\Theta=-(\rho_{\parallel}-\rho)/(\rho_{\perp}-\rho),$$

where Θ is the angle between the domain magnetization **M** and the ribbon axis and, hence, the current density **J**, we find from our data at 10 K that $\Theta=38.4°$, 37.3°, and 34.7° for $x=0$, 6, and 12, respectively. Indeed Mössbauer, scanning electron microscopy, and ferromagnetic resonance techniques[16] have established, for $x=0$, that **M** lies in the plane of the ribbon and that the value of $\Theta\simeq 30°$. Thus, our analysis indicates that the replacement of B by Si does not change this special orientation of **M**.

The high-field slope ($\rho^{-1}d\rho/dH$), found by a least-squares-fit program, for all the samples is negative at all temperatures, its magnitude is larger for the $\perp$ orientation. This is shown in Fig. 6(b) for some cases. In general, the magnitude dc of the slope[15] should increase with increasing temperature since electron-magnon scattering could be effectively reduced as magnons are quenched at higher fields. Its value is proportional to the high-field magnetic susceptibility[11] which decreases with decreasing temperature. However, we find here that, although the slope does not strongly depend on temperature, it has a small increase to the contrary. The large slope at lower temperatures thus implies the lack of complete alignment of spins even at 10 K ($T\ll T_c$). We do find from our dc-magnetization measurements that, for $x=0$, the high-field (15 kOe) susceptibility is as high as 1.12×10^{-4} cm^3/g at 10 K and not too different from 1.15×10^{-4} cm^3/g at 180 K. This observation of increasing slope with decreasing temperature is rather common in Fe-based alloys having Invar properties.[1] However, Fig. 6(b) shows that the addition of Si suppresses this effect since the slope does not decrease significantly at higher temperatures.

The raw $R(T)$ data for the $x=6$ alloy at constant fields of 2,7, and 14 kOe are plotted in Fig. 7. We observe that

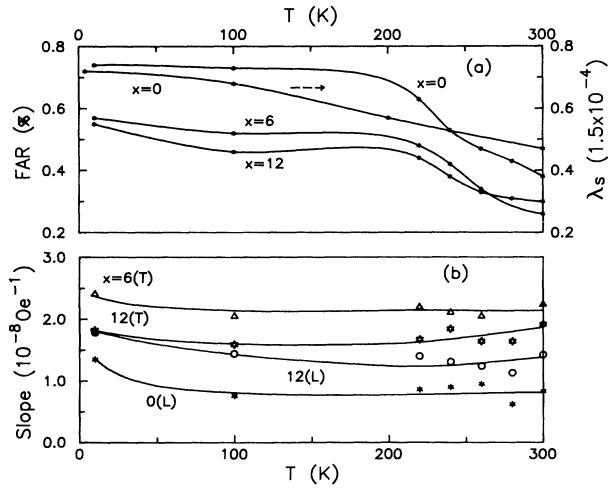

FIG. 6. (a) Ferromagnetic anisotropy of resistivity (FAR) vs temperature for $x=0$, 6, and 12. Linear magnetorestriction coefficient λ_s is also shown for $x=0$. (b) High-field slope ($\rho^{-1}d\rho/dH$) vs temperature for $x=0$, 6, and 12 for some orientations. L and T in brackets refer to longitudinal and transverse orientations, respectively.

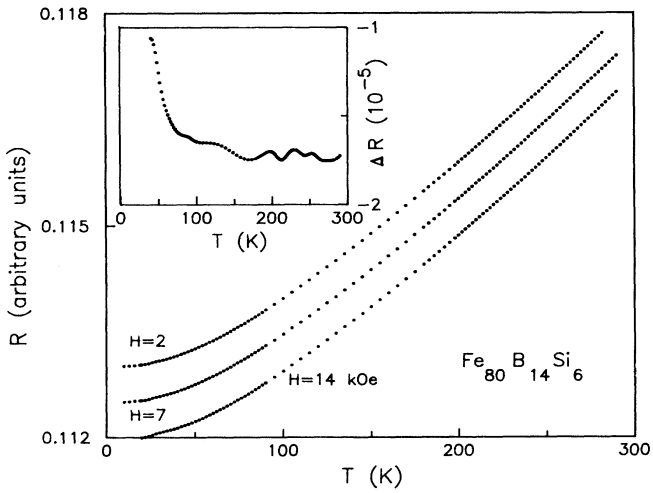

FIG. 7. Temperature dependence of electrical resistance $R(T)$ at constant external magnetic fields of 2, 7, and 14, kOe for $x=6$. The curves are shifted along the R axis for clarity. The inset shows $\Delta R=R(T,\ 14\ \text{kOe})-R(T,\ 7\ \text{kOe})$ vs temperature.

TABLE II. Magnetic field dependence of the coefficients of the magnetic terms [Eqs. (4b) and (5b)] in $Fe_{80}B_{20-x}Si_x$ ($x=0$, 6, and 12) amorphous ferromagnets. L is $\mathbf{J}\|\mathbf{M}$ and T is $\mathbf{J}\perp\mathbf{M}$.

x (at. %)	Range of fit: 35–85 K $10^6\alpha_{3/2}$ ($K^{-3/2}$) H (kOe)			Range of fit: 200–300 K $10^6\alpha'_{3/2}$ ($K^{-3/2}$) H (kOe)		
	2	7	14	2	7	14
0 (L)	3.4	3.3	3.2	3.9	3.9	4.0
0 (T)	2.1	2.1	2.0	4.8	4.8	4.8
6 (L)	4.0	3.9	3.8	5.2	5.3	5.3
6 (T)		4.9	4.8		5.8	5.8
12 (L)	4.5	4.5	4.3			

the resistance decreases with increasing magnetic field for external fields above technical saturation. This is in agreement with the negative slope observed in Fig. 5 at all temperatures. It must be emphasized here that the data at lower fields are affected by the FAR due to the domain structure and, hence, must be avoided in the analysis of magnetic scattering. The effect of the magnetic field on R is very small, a field difference of 10 kOe changes R by 0.02% only. So, in Fig. 7 the curves are shifted along R axis so that the difference between them shows up. In the inset of Fig. 7, the difference R (T, 14 kOe)$-R$ (T, 7 kOe) has been plotted against temperature.

The $r(T)$ data at constant magnetic fields of 2, 7, and 14 kOe were analyzed in a manner similar to the zero-field case using the same least-squares-fit program. We find that the data fits equally well ($\chi^2 \simeq 10^{-10}$) to Eqs. (4) and (5) even in the presence of external magnetic fields. This proves that the temperature dependence of the resistivity is still described by the same equations. However, the coefficients for the magnetic terms only show some field dependence at low temperatures, as is evident from Table II. The inset of Fig. 7 also shows that the difference between the data (say, 14 and 7 kOe) initially increases with temperature and then remains more or less constant at higher temperatures. This could be qualitatively understood as follows: The incoherent electron-magnon scattering term, giving $+\alpha_{3/2}(H)T^{3/2}$ dependence, should be smaller at higher fields because of the quenching of the magnons resulting in less electron-magnon scattering. This implies that $\alpha_{3/2}$ should decrease with field as is observed at lower temperatures (35–85 K). At higher temperatures (200–300 K), the other term $-\alpha_{3/2}(H)T^{3/2}$ [see discussion after Eq. (3)] will not decrease that much at higher magnetic fields since the magnetic moment itself increases with field. Thus, the resultant coefficient $\alpha_{3/2}$ may not change with field. This does not happen at lower temperatures because the change of magnetic moment is much less for $T \ll T_C$.

V. CONCLUSIONS

Our quantitative analysis of the electrical resistivity data in $Fe_{80}B_{20-x}Si_x$ ferromagnets shows conclusively that the inclusion of magnetic terms improves χ^2 by an order of magnitude. If interpreted in terms of a T^2 term, the coefficients agree quantitatively with those of Kaul *et al.*[7] in a similar system, viz., $Fe_{80}B_{20-x}C_x$ and yields realistic Θ_D, 330±40 K. However, we find that there could be an equally good fit (actually much better) for $T \ll \Theta_D$ in terms of a $T^{3/2}$ term as predicted by Richter *et al.*,[3] except for the disturbing fact that the resulting Θ_D has a wide range of values in this series. A possible explanation is offered in terms of the applicability of the theory Richter *et al.*,[3] [Eq. (3)] which may not satisfy the condition $T \ll T_C$ for $T \geq \Theta_D$. It is therefore safe to conclude that the magnetic contribution at low temperatures at least, viz., $T \ll \Theta_D$, occurs through a $T^{3/2}$ term which is in agreement with the theoretical prediction.[3]

Magnetoresistance measurements up to 16.5 kOe at several constant temperatures (10–300 K) show a positive ferromagnetic anisotropy of resistivity in these amorphous ferromagnets, very similar to the crystalline case. The FAR decreases with increasing temperature as expected in a ferromagnet. At higher fields (≥ 2 kOe), the magnetoresistance is very small and negative for both orientations at all temperatures. The temperature dependence of the electrical resistivity in the presence of a magnetic field is still described by the same set of equations as in the case of zero field. However, the coefficient of the magnetic term decreases somewhat with increasing field at lower temperatures while remaining constant with increasing field at higher temperatures.

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[1]N. Banerjee, R. Roy, A. K. Majumdar, and R. Hasegawa, Phys. Rev. B **24**, 6801 (1981); R. Roy and A. K. Majumdar, *ibid.* **31**, 2033 (1985).

[2]S. R. Nagel and J. Tauc, Phys. Rev. Lett. **35**, 380 (1975).

[3]R. Richter, M. Wolf, and F. Goedsche, Phys. Status Solidi B **95**, 473 (1979).

[4]Béla Vasvári, Physica B **159**, 79 (1989).

[5]G. Bergmann and P. Marquardt, Phys. Rev. B **17**, 1355 (1978).

[6]G. Thummes, J. Kötzler, R. Ranganathan, and R. Krishnan, Z. Phys. B **69**, 489 (1988).
[7]S. N. Kaul, W. H. Kettler, and M. Rosenberg, Phys. Rev. B **33**, 4987 (1986).
[8]E. Babic, Z. Marohnic, M. Ocko, A. Hamzic, K. Saub, and B. Pivac, J. Magn. Magn. Mater. **15**, 934 (1980).
[9]W. H. Kettler and M. Rosenberg, Phys. Rev. B **39**, 12 142 (1989).
[10]A. K. Majumdar and G. Uffinger, Solid State Commun. **51**, 967 (1984).
[11]A. K. Nigam and A. K. Majumdar, Physica B **95**, 385 (1978).
[12]J. Smit, Physica **16**, 612 (1951).
[13]M. Mitera, M. Naka, T. Masumoto, N. Kazama, and K. Watanabe, Phys. Status Solidi A **49**, K163 (1978).
[14]R. C. O'Handley, M. C. Narasimhan, and M. O. Sullivan, J. Appl. Phys. **50**, 1633 (1979).
[15]J.-P. Jan, in *Solid State Physics,* edited by F. Seitz and D. Turnbull (Academic, New York, 1957), Vol. 5, p. 1.
[16]R. Hasegawa, R. C. O'Handley, and L. I. Mendelsohn, in *Magnetism and Magnetic Materials—1976 (Joint MMM-Intermag Conference, Pittsburgh),* Partial Proceedings of the First Joint MMM-Intermag Conference, edited by J. J. Becker and G. H. Lander (AIP, New York, 1976), p. 298.