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Electrical and galvanomagnetic properties of $Fe_{100-x}B_x$ metallic glasses ($13 \le x \le 26$)

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The concentration dependence of the absolute value of electrical resistivity ρ at room temperature, the ferromagnetic anisotropy of the resistivity (FAR) (at 300 and 77 K), and the spontaneous Hall constant R_s (at 300 and 77 K) for $Fe_{100-x}B_x$ ($13 \le x \le 26$) are discussed for the first time in the same set of alloys. Theoretical calculations are made to clarify the nature of the resistivity variation with boron concentration. The trend of increasing ρ with increasing x is shown from both theory and experiments. The relation between FAR and the saturation magnetic moment M_s for this series is established once again and a possible explanation is suggested for the sharpening of the peak in FAR versus x plots with decreasing temperature. R_s shows a peak around $x = 18$ and hence the lack of validity for the most commonly used correlation $R_s = A\rho^n$ is pointed out for this series. It is clearly shown that the dominant mechanism for magnetoresistance in these metallic glasses is the usual ferromagnetic anisotropy of resistivity.

I. INTRODUCTION

Amorphous ferromagnetic metallic alloys are particularly attractive because of their low cost, soft magnetism, and good mechanical properties. In recent years the study of the electronic and transport properties of these systems has been a subject of wide interest. The most significant experimental results reported recently are the large absolute values of the electrical resistivity, the very small temperature coefficient of resistivity, very small values for the ferromagnetic anisotropy of resistivity, and nearly temperature-independent anomalous Hall coefficients. The behaviors characteristic of these alloys are attributed to the lack of periodic atomic arrangement in the amorphous state but the detailed mechanisms are not yet completely understood.

In the present investigation we have chosen a very simple transition-metal-metalloid metallic glass series, namely, $Fe_{100-x}B_x (13 \le x \le 26)$. Characterization of such binary metallic glasses is important for understanding the properties of more complicated amorphous systems. We have studied the absolute values of the electrical resistivity, the ferromagnetic anisotropy of resistivity (FAR), and the Hall effect in the Fe-B series. The temperature dependence of the resistivity has already been studied by us in the same series.[1] All these experiments were done on $Fe_{100-x}B_x (13 \le x \le 26)$ manufactured by the Allied Chemical Corp. Since the composition range is rather wide it is ideal for studying the composition dependence of the above galvanomagnetic properties. Also, any correlation and comparison of physical properties are meaningful if various measurements are made on the same set of samples. This is especially true for metallic glasses.

The variations of the absolute values of the resistivity ρ, the spontaneous Hall constant R_s, and the spontaneous Hall conductivity γ_{H_s} with the boron concentration x are reported for the first time in this work. The results of magnetoresistance measurements are also included. The anisotropic magnetoresistance $(\rho_{\parallel} - \rho_{\perp})$, being an inherent material property, does not depend on the initial magnetic domain structure and remains unchanged by heat treatment, etc. Thus one can compare other magnetic properties in terms of this quantity.[2–4] The angle θ between the spontaneous magnetization M_s and the ribbon axis for the whole series is also reported for the first time. We have tried to find out some new results for amorphous Fe from extrapolation of our magnetoresistance and resistivity data. An attempt is made to explain physically all these properties in terms of structure, other physical properties, and Invar anomalies in the Fe-B series.

II. THEORY

A. Resistivity

Considering amorphous metallic glasses as frozen liquids, one can apply Ziman's theory of liquid metals to calculate the temperature and composition dependence of the electrical resistivity as given by[5]

$$\rho = \frac{30\pi^3\hbar^3}{me^2k_F^2E_F\Omega}\sin^2[\eta_2(E_F)] \times \{1+[S_0(2k_F)-1]e^{-2[W(T)-W(0)]}\}\ , \tag{1}$$

where k_F is the Fermi wave vector, Ω is the atomic volume, $W(T)$ is the Debye-Waller factor at a temperature T, $\eta_2(E_F)$ is the $l = 2$ partial-wave phase shift at the Fermi energy E_F, $S_0(2k_F)$ is the structure factor at 0 K, corresponding to $k = 2k_F$ and $\hbar$, and m and e have their usual meaning. The asymptotic temperature dependence of $W(T)$ in the Debye approximation is given by

$$W(T) = \begin{cases} W(0)+4W(0)\frac{1}{6}\pi^2(T/\Theta_D)^2, & T \ll \Theta_D & (2) \\ W(0)+4W(0)(T/\Theta_D), & T \ge \Theta_D & (3) \end{cases}$$

where

$$W(0)=\frac{3}{8}\frac{\hbar^2 k_F^2}{M k_B \Theta_D} . \tag{4}$$

M is the atomic weight, k_B is the Boltzmann constant, and Θ_D is the Debye temperature. In calculating the resistivity of metallic glasses as a function of composition, we assume that $\sin^2\eta_2(E_F)$ and Ω are approximately the same for the whole series. Then, using $E_F \propto k_F^2$, we can write Eq. (1) as

$$\rho=\frac{C}{k_F^4}\{1+[S_0(2k_F)-1]e^{-2[W(T)-W(0)]}\} , \tag{5}$$

where C takes care of the constants. Since we are calculating the room-temperature resistivity, in Eq. (5) we use $W(T)-W(0)$ from Eq. (3). Then Eq. (5) can be written as

$$\rho=\frac{C}{k_F^4}\left[S_0(2k_F)+8W(0)\frac{T}{\Theta_D}[1-S_0(2k_F)]\right] . \tag{6}$$

B. Magnetoresistance

The electrical resistivity of a polycrystalline ferromagnet depends on the angle between the current density $\vec{J}$ and the magnetization vector $\vec{M}$. The longitudinal magnetoresistance ($\vec{J}\,||\,\vec{M}$) is positive while the transverse one ($\vec{J}\perp\vec{M}$) is negative at low fields. The FAR is given by

$$R_{\mathrm{FAR}}=\frac{\Delta\rho}{\rho_0}=\frac{\rho_{||}-\rho_{\perp}}{\rho_0} , \tag{7}$$

where ρ_0 is the resistivity in the demagnetized state. ρ_0 could be expressed as

$$\rho_0=\rho_{\perp}\sin^2\theta+\rho_{||}\cos^2\theta , \tag{8}$$

where θ is the angle between the current and magnetization direction. Hence, the longitudinal magnetoresistance is

$$\Delta\rho_{||}/\rho_0=\frac{\rho_{||}-\rho_0}{\rho_0}=\frac{\rho_{||}-\rho_{\perp}\sin^2\theta-\rho_{||}\cos^2\theta}{\rho_0}$$

$$=\frac{\rho_{||}-\rho_{\perp}}{\rho_0}\sin^2\theta ,$$

or

$$\Delta\rho_{||}/\rho_0=R_{\mathrm{FAR}}\sin^2\theta . \tag{9}$$

Similarly, the transverse magnetoresistance is

$$\Delta\rho_{\perp}/\rho_0=-R_{\mathrm{FAR}}\cos^2\theta . \tag{10}$$

From Eqs. (9) and (10) we obtain

$$R_{\mathrm{FAR}}=\Delta\rho_{||}/\rho_0-\Delta\rho_{\perp}/\rho_0$$

and

$$\cot^2\theta=\frac{-\Delta\rho_{\perp}/\rho_0}{\Delta\rho_{||}/\rho_0} .$$

As shown by Nigam and Majumdar,[6] in the case of metallic glasses $\rho_0\simeq\rho$, where ρ is the resistivity measured in zero external field ($H_{\mathrm{ext}}=0$) and hence

$$R_{\mathrm{FAR}}=\Delta\rho_{||}/\rho-\Delta\rho_{\perp}/\rho \tag{11}$$

and

$$\cot^2\theta=\frac{-\Delta\rho_{\perp}/\rho}{\Delta\rho_{||}/\rho} . \tag{12}$$

Also the anisotropic magnetoresistance $\rho_{||}-\rho_{\perp}$ can be written as

$$\rho_{||}-\rho_{\perp}=(\Delta\rho_{||}/\rho-\Delta\rho_{\perp}/\rho)\rho . \tag{13}$$

In Eqs. (11)–(13) $\Delta\rho_{||}/\rho$ and $\Delta\rho_{\perp}/\rho$ are obtained by extrapolating the $\Delta\rho/\rho$ versus H_{ext} curves to H_{demag}, such that $H_{\mathrm{int}}=0$.

Bhonke *et al.*[7] have shown that $\Delta\rho/\rho$ varies as $T^{3/2}$. The magnetic moment M_s (μ_B/Fe atom) also varies as $T^{3/2}$.[8] Considering these two observations, Bhonke *et al.* have suggested a relationship between them as

$$\Delta\rho/\rho=AM_s^m , \tag{14}$$

where M_s is saturation magnetic moment per Fe atom and A and m are constants.

C. Hall effect

The Hall resistivity ρ_H in a polycrystalline ferromagnet can be written as[9]

$$\rho_H=E_Y/J_X=R_0B_z+R_sM_z , \tag{15}$$

where $\vec{J}\,||\,\hat{X}$ is the electric current density, $\vec{E}$ the electric field, and $\vec{B}\,||\,\hat{Z}$ the magnetic induction. The first term has its origin in the Lorentz force acting on the conduction electrons, and is present in nonmagnetic materials also. R_0 is the coefficient of the ordinary Hall effect. The second term depends on the magnetization and is a characteristic property of ferromagnets. The coefficient R_s is called the extraordinary or the spontaneous Hall constant.

The spontaneous Hall effect depends on the magnetization, that is, on electron spin, and since the spin must influence the transport process, this effect should depend on the spin-orbit interaction.[10] This effect also depends on the scattering potentials created by impurities, phonons, magnons, etc.

In ferromagnets, at ordinary temperatures R_s is much larger than R_0 and can be written as[9]

$$R_s=A\rho^n \ (n\simeq 2) , \tag{16}$$

where A is a constant depending on the metal but not on the temperature, and ρ is the resistivity. This relation, if valid, clearly shows that the spontaneous effect is connected with the electron scattering. In metallic glasses, the validity of this relation ($R_s\propto\rho^2$) is difficult to confirm experimentally because of the weak temperature dependence of R_s and ρ, and also because small variations in metalloid content have comparatively little effect on the resistivity, which is dominated more by disorder.

Nevertheless, in Sec. IV we tried to find out the validity of this relation by comparing the concentration (x) dependence of R_s and ρ. The Hall conductivity γ_{H_s} given by

$$\gamma_{H_s}=\frac{\rho_H}{\rho^2}=\frac{R_s M_s}{\rho^2} \tag{17}$$

becomes almost independent of temperature or concentration if Eq. (16) is valid for R_s.

D. Correlation between magnetoresistance and Hall effect

When a dc is passed perpendicular to the domain walls, due to domain-wall scattering, the Ohmic resistivity of the sample is expected to increase. In a uniaxial ferromagnet, where the resistivity tensor has an off-diagonal Hall component, Berger[11] has calculated, from Maxwell's equations in the neighborhood of 180° domain walls, that there is an increase in Ohmic resistivity. When a magnetic field parallel to the easy axis removes the domain walls, a negative magnetoresistance results which is given by (assuming wall spacing $\ll$ sample width)

$$\Delta\rho/\rho'=-\beta^2\ . \tag{18}$$

Here ρ' is the resistivity in the absence of walls and β is the tangent of the Hall angle Φ_H and is given by

$$\beta=\tan\Phi_H=\frac{\rho_H}{\rho_\perp}\ . \tag{19}$$

On the basis of this theory, Majumdar and Nigam[12] have formulated a correlation between magnetoresistance and the Hall effect given by (taking the above mechanism as well as the usual ferromagnetic anisotropy of resistivity)

$$\beta^2=-\left[\frac{\Delta\rho_\perp}{\rho}+\frac{\Delta\rho_\parallel}{\rho}\cot^2\theta\right], \tag{20}$$

where $\Delta\rho_\perp/\rho$ and $\Delta\rho_\parallel/\rho$ are the transverse and longitudinal magnetoresistance, respectively, and θ is the angle between the current and magnetization direction.

III. EXPERIMENTAL

The Fe-B samples were in the form of thin ribbons, typically 1 mm wide and 30 μm thick, and were cut to $\sim$15 mm length, for all the measurements. The resistance at room temperature was measured by a model 1608-A impedence bridge (General Radio). This bridge has an accuracy of 0.1% if the resistance is between 1 Ω and 1 MΩ. The length and weight of the same piece of samples were measured and the density of these samples were taken from the data of Hasegawa and Ray.[13] Thus, the absolute values of resistivity of these samples were calculated from these measured quantities. The error in the resistivity values ($\sim$3–15%) is introduced mainly by the inaccuracy involved in the measurements of weight and length.

The ferromagnetic anisotropy of resistivity at 300 K and liquid N_2 temperature (77 K) was measured by a four-probe dc method described elsewhere.[14] For both the transverse and longitudinal magnetoresistance measurements the orientation of the sample was such that the applied field H_{ext} was parallel to the ribbon plane. A resistivity change of a few parts per million could be detected in our measurements.

A fiber-glass-reinforced plastic sample holder was specially designed for the measurements of Hall resistivity at 300 and 77 K. Arrangements were made to have pressure contacts for the two current probes. Because of the irregularity of the width of these samples, it was very difficult to use pressure contact for both the Hall voltage probes. Also, because the samples were very thin, they formed a ridge if the pressure was applied from both sides across the width of the samples. Keeping this in mind, one of the voltage probes was soldered with low-melting-point Cerroseal-35 solder and a pressure contact was used for the other voltage probe to minimize the misalignment voltage. This sample holder was then enclosed in a cryostat which was placed in a Varian 15 in. electromagnet in such a way that the applied field, H_{ext}, was perpendicular to the sample plane. The Hall voltages V_H were directly read on a Keithley 148 nanovoltmeter under the reversal of both currents and magnetic fields to eliminate thermal and misalignment voltages, respectively. The spontaneous Hall constant R_s was calculated from the low-field slope of the ρ_H $(=V_H t/I$, where t represents thickness of the sample and I is the sample current) versus the H_{ext} plot, i.e.,

$$R_s=\left[\frac{\partial\rho_H}{\partial H_{\text{ext}}}\right]_{H_{\text{ext}}\to 0}\quad\text{for } T<T_c\ .$$

The measurements on different pieces of the same sample and also on the same piece were repeated several times. The Hall voltages V_H at different field values were quite reproducible in these runs. The error of $\sim$5–10% in the values of R_s mainly comes from the uncertainty in the measurement of the thickness of these samples which are very nonuniform.

The final values quoted here are the averages of the values obtained in two or three different measurements. This also includes the sample-to-sample variation.

IV. RESULTS AND DISCUSSION

A. Resistivity

In Fig. 1 we have plotted the absolute value of the resistivity ρ at 300 K against x, the boron concentration. The experimental data show an increase of ρ with increasing boron content. The total variation of ρ over the entire composition range is $\sim$30%. Theoretically, ρ can be calculated from Eq. (6). The values of $W(0)$ for the $\text{Fe}_{100-x}\text{B}_x$ series are obtained from Eq. (4) using k_F, M, and Θ_D (see Appendix I) as found in an earlier work.[1] Although it is very difficult to obtain a precise estimate of $S(2k_F)$ from $S(k)$ versus a k graph,[15] we still have to take account of its variation with x because it plays a significant role in Eq. (6). The values of resistivity thus calculated also increases with increasing x as shown by the theoretical curve in Fig. 1 for comparison.

Fukamichi *et al.*[16] have also studied the variation of absolute values of ρ with concentration x in $\text{Fe}_{100-x}\text{B}_x(14\le x\le 22)$ metallic glass series. They too have found an increase in resistivity with increasing x, but

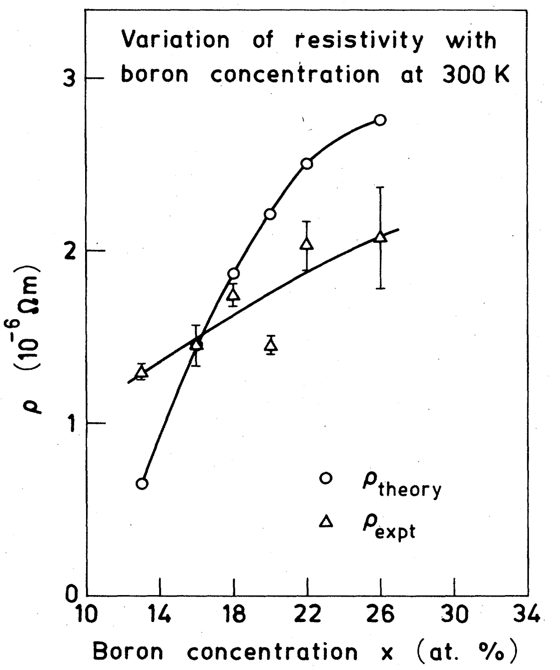

FIG. 1. Experimentally found resistivity ρ_{expt} and theoretically calculated resistivity ρ_{theory} at room temperature vs x, the boron concentration for Fe-B metallic glasses in the range $13 \le x \le 26$.

their samples show a variation of 10% in the range ($14 \le x \le 22$). As it is clear from Fig. 1, the theoretical curve shows a rather sharp change over the entire range of composition. This overestimation of ρ might be a result of overestimating the structure factor $S(2k_F)$, which is (as mentioned earlier) very difficult to estimate precisely from the available plots. An additional error in calculating ρ may also come from the fact that we have taken the values of $S(2k_F)$ of a different set of samples, prepared under different conditions [Fukunaga *et al.*[15] measured $S(k)$ on splat-cooled Fe-B amorphous alloys, whereas the alloys which we have used are melt-spun]. Also, according to Eq. (6), we needed the values of $S_0\,(2k_F)$, i.e., $S(k)$ at 0 K, but the available data were taken at room temperature. Still, in the absence of exact values of $S_0\,(2k_F)$, we have used these structure-factor plots to compute theoretically the behavior of ρ. Hence, our theoretical plot of ρ versus x should be taken just as a guide to show whether ρ decreases or increases with x.

The main contribution of the electrical resistivity of pure transition metals arises from resonance scattering. The addition of metalloid atoms increases the number of conduction electrons and thus increases k_F. Because of this addition the structure factor $S(k)$ plays a significant role in the resistivity of metallic glasses. With increasing x (boron content), $2k_F$ moves more towards K_p (the most probable nearest-neighbor distance in K space) and thus increases the value of the resistivity.

B. Ferromagnetic anisotropy of resistivity (FAR)

In Fig. 2, we have shown a typical result of our magnetoresistance measurements. At low fields, the longitudinal magnetoresistances, $\Delta\rho_{\parallel}/\rho$, are all positive and rise rather fast with increasing field, whereas the transverse ones, $\Delta\rho_{\perp}/\rho$ (in magnitude always larger than $\Delta\rho_{\parallel}/\rho$), are all negative and drop much slower with increasing field. At higher fields both of them show negative slopes due to less electron-magnon scattering.

We would like to point out here that, in measurements of the transverse magnetoresistance, the sample alignment with respect to the magnetic field plays an important role at low fields. If the sample is misaligned, the transverse magnetoresistance at low fields will show positive values, as observed by Fukamichi *et al.*[2] and Kern and Gonser.[17] They have attributed this positive value to the initial orientation of some of the domains in the direction perpendicular to the field and parallel to the current. However, according to our observations, this sort of positive value of $\Delta\rho_{\perp}/\rho$ will show up in the magnetoresistance measurements, in both possible orientations of the field with respect to the ribbon plane [(i) $\vec{H}$ perpendicular to the ribbon plane and (ii) $\vec{H}$ parallel to the ribbon plane], only if the alignment of the sample is wrong. Since longitudinal magnetoresistance, $\Delta\rho_{\parallel}/\rho$, saturates much faster with field than $\Delta\rho_{\perp}/\rho$, even a slight misalignment will introduce a positive value which overshadows the inherent negative value of $\Delta\rho_{\perp}/\rho$. The only merit of choosing the second type of orientation is that this spurious positive transverse magnetoresistance will be much smaller in this orientation because of the small value of the demagnetizing factor. Hence, it is much easier to avoid the misalignment effect in this orientation.

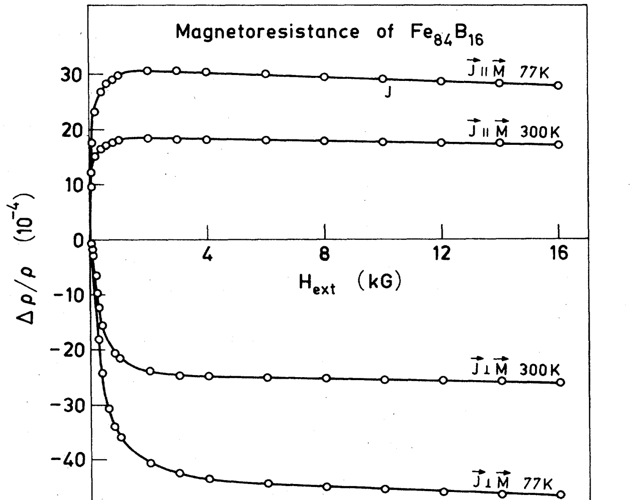

FIG. 2. Magnetoresistance $\Delta\rho/\rho$ against external magnetic field H_{ext} for a typical sample $Fe_{84}B_{16}$ for longitudinal ($\vec{J} \parallel \vec{M}$) and transverse ($\vec{J} \perp \vec{M}$) orientations at 77 and 300 K.

As shown in Fig. 3, the $R_{\mathrm{FAR}} = \Delta\rho/\rho$ versus x plot shows at room temperature a broad maximum around $x = 16$, in agreement with the results obtained by Fukamichi *et al.*[2] This maximum, again at $x = 16$, becomes more prominent at the lower temperature of 77 K. This type of characteristic variation of FAR with concentration is quite similar to the variation of many other physical properties like density,[13,15] magnetorestriction,[18] coordination number,[15,19] magnetic moment,[20] etc. Kemény *et al.*[21] have shown that even the crystallization process changes from a two-step mechanism to a one-step mechanism as boron content x changes from $x \leq 15$ to $x \geq 15$. From Eq. (14) it is clear that a peak in the magnetic moment versus x plot implies a peak in the R_{FAR} versus x graph. If we use M_s at 4.2 K (Ref. 20) in this series for correlating it to our FAR data at 77 K (M_s at 77 K will not be much different from that at 4.2 K), the log-log plot between R_{FAR} and M_s shows a straight line. Equation (4) is thus well verified for this series and we obtain $m = 27$ and $A = 5.3 \times 10^{-12}$. In these metallic glasses the peak in the M_s versus x plot becomes smeared out with increasing temperature. So, from Eq. (14), a similar behavior is also expected in the R_{FAR} versus x graph with a more prominent peak. It is clear from Fig. 3 that our R_{FAR} versus x plot at room temperature is broader as compared to that at 77 K.

From Figs. 1 and 3 we have tried to predict the FAR and the resistivity of amorphous Fe at 300 K by extrapolating these plots to $x = 0$. Our results show that the FAR of amorphous Fe is negative $\sim -0.4\%$ (for crystalline Fe it is $+0.5\%$) and the resistivity of amorphous Fe, $\rho_{a\text{-Fe}}$ is found to be $\simeq 1 \times 10^{-6}\ \Omega\,\mathrm{m}$ (as compared to the $\rho_{\mathrm{cry\ Fe}} = 10^{-7}\ \Omega\,\mathrm{m}$).

Table I gives the values of the longitudinal and transverse magnetoresistances $\Delta\rho_{\parallel}/\rho$, $\Delta\rho_{\perp}/\rho$, and the FAR for all the samples at 300 and 77 K. Table II shows the θ values calculated from Eq. (12) with the help of $\Delta\rho_{\parallel}/\rho$ and $\Delta\rho_{\perp}/\rho$ (given in Table I). It can be seen that θ values calculated by this equation lie between 30°–40°, in accordance with the values given by Bhonke *et al.*[7] and Hasegawa, O'Handley, and Mendelsohn.[22]

C. Hall-effect studies

In Fig. 4 we have plotted R_s and γ_{H_s} at room temperature, as functions of the boron content x. It is clear that R_s, like many other properties of Fe-B glassy alloys, shows a peak around $x = 18$, whereas γ_{H_s} falls sharply around $x = 20$.

O'Handley[23] has discussed the spontaneous Hall coefficient R_s of amorphous $\mathrm{Fe_{80}B_{20}}$. It is argued that R_s of $\mathrm{Fe_{80}B_{20}} \propto \rho^2$ because it falls on a universal R_s versus ρ graph. It also seems to satisfy the relation $\Delta y \propto R_s/\rho^2$ (Δy is the magnitude of the side jump) by giving $\Delta y \simeq 1 \times 10^{-10}$ m, comparable to that of crystalline transition-metal alloys (also $\simeq 10^{-10}$ m). This agreement between Δy values and the point for $\mathrm{Fe_{80}B_{20}}$ falling on the R_s versus ρ graph for crystalline materials seems to be a mere coincidence. As can be seen from Figs. 1 and 4, R_s does not vary as ρ^n. In fact this relation given by Eq. (16) ($R_s = A\rho^n$) makes the assumption that any band-structure differences due to the additives are negligible, the alloys are dilute ($\sim 5\%$), and R_s is governed mainly by scattering. As shown by Suzuki *et al.*,[15] the composition dependence of the coordination number, the density, and the binding energy of the Fe $3d$ band clearly show that around the composition range from 14 to 16 at. % boron, there is a drastic modification in the topological arrangement of the Fe atoms in the Fe-B glassy alloys. These studies suggest that the B atoms occupy an interstitial po-

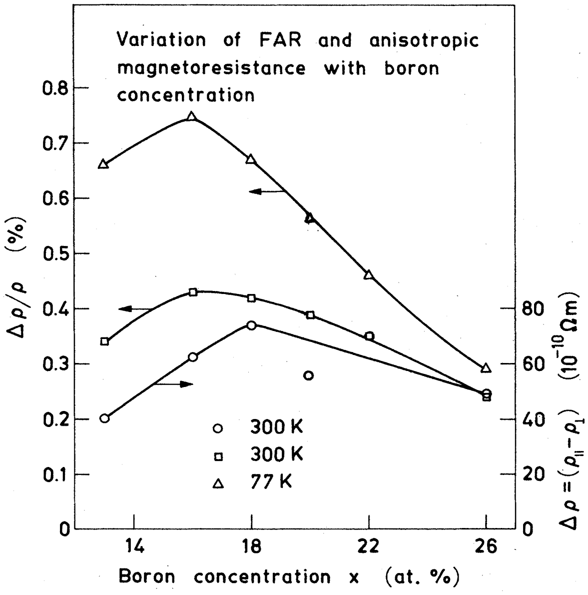

FIG. 3. FAR vs the boron concentration x ($13 \leq x \leq 26$) at 77 and 300 K and the anisotropic magnetoresistance ($\rho_{\parallel} - \rho_{\perp}$) vs x at 300 K.

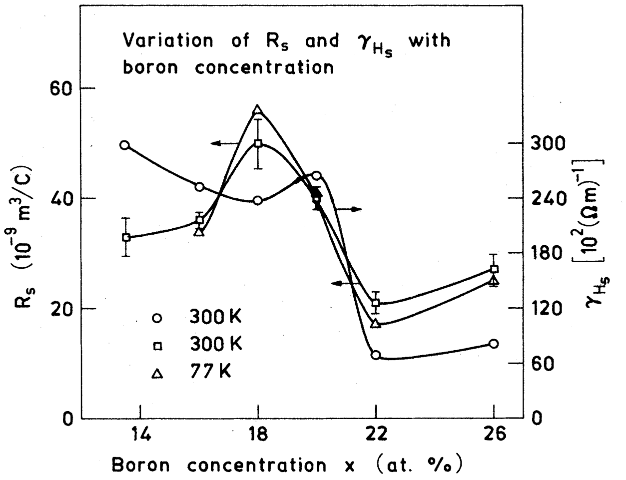

FIG. 4. Spontaneous Hall constant R_s vs the boron concentration x ($13 \leq x \leq 26$) at 77 and 300 K and the variation of γ_{H_s} with boron concentration x at 300 K.

TABLE I. Values of longitudinal magnetoresistance $\Delta\rho_{\parallel}/\rho$, transverse magnetoresistance $\Delta\rho_{\perp}/\rho$, R_{FAR} spontaneous Hall coefficient R_s at 300 and 77 K, resistivity ρ, anisotropic magnetoresistance $(\rho_{\parallel}-\rho_{\perp})$, saturation magnetization M_s (Ref. 24), and Hall conductivity γ_{H_s} at 300 K of $Fe_{100-x}B_x$ samples.

	Room temperature (300 K)								Liquid-nitrogen temperature (77 K)			
x (at. %)	$\Delta\rho_{\parallel}/\rho$ (10^{-4})	$\Delta\rho_{\perp}/\rho$ (10^{-4})	R_{FAR} (%)	ρ $(10^{-6}\ \Omega\,\mathrm{m})$	$(\rho_{\parallel}-\rho_{\perp})$ $(10^{-10}\ \Omega\,\mathrm{m})$	R_s $(10^{-9}\ \mathrm{m}^3/C)$	M_s (T)	γ_{H_s} $[10^2\ (\Omega\,\mathrm{m})^{-1}]$	$\Delta\rho_{\parallel}/\rho$ (10^{-4})	$\Delta\rho_{\perp}/\rho$ (10^{-4})	R_{FAR} (%)	R_s $(10^{-9}\ \mathrm{m}^3/C)$
13	13.2	−20.8	0.34	1.3 ±0.04	40.2	33±1	1.52	297	19.6	−46.2	0.66	
16	18.2	−24.6	0.43	1.45±0.12	62.1	36±1	1.47	252	31.0	−43.0	0.74	34±1
18	13.9	−28.4	0.42	1.74±0.07	73.5	50±5	1.43	236	22.6	−44.7	0.67	56±5
20	12.3	−26.3	0.39	1.45±0.04	56.0	40±2	1.38	263	19.9	−36.1	0.56	41±2
22	11.2	−23.5	0.35	2.03±0.14	70.4	21±2	1.37	70	15.2	−31.2	0.46	17±2
26	5.5	−18.6	0.24	2.07±0.31	49.8	27±3	1.30	82	7.5	−20.6	0.28	25±3

TABLE II. Values of θ, the angle between current and magnetization (from magnetoresistance measurements), and β, the tangent of the Hall angle (from Hall effect and resistivity measurements) of $Fe_{100-x}B_x$ samples.

x (at. %)	$\beta=\tan\phi_H=\rho_H/\rho$ (10^{-2})	θ
13	3.86	38.9°
16	3.65	40.7°
18	4.11	34.9°
20	3.81	34.4°
22	1.42	34.6°
26	1.70	28.6°

sition in the low boron-content alloys and with increasing boron content, these atoms take the substitutional positions in the alloy. Thus the band structure is severely altered around the eutectic composition, and hence Eq. (16) should not hold for these alloys.

Now, in $Fe_{100-x}B_x$, boron is nonmagnetic and hence with decreasing boron concentration we expect an increase in R_s. As is clear from Fig. 4, between $x=26$ and 18 R_s increases with decreasing x as expected, but for $13 \le x \le 18$ there is a fall in the R_s values. This sort of unexpected behavior of R_s for alloys $x \le 18$ can be explained by the Invar anomaly of Fe-B glassy alloys. Fukamichi *et al.*,[24] Hasegawa and Ray,[25] and Hiroyoshi *et al.*[20] have shown that the Fe-B alloys show Invar characteristics around $13 \le x \le 17$ at. % boron. Also, the specific-heat study of these alloys by Matsuura *et al.*[26] shows an unusually large value of γ (the electronic specific-heat coefficient) far exceeding the band-structure contribution. They attribute this unexpectedly large γ value for the B-poor alloys, to the ferromagnetic instability, or magnetic inhomogeneity closely related to the occurrence of Invar effect. Keeping in mind our R_s versus x plot, we suggest that due to the occurrence of Invar characteristics in this series of alloys around $x=18$, the R_s values start falling. The unexpected behavior of the Hall conductivity γ_{H_s} (R_sM_s/ρ^2) automatically follows from the unexpected type of dependence of R_s on ρ.

D. Correlation between Hall effect and magnetoresistance

The correlation given by Eq. (20) could not be established in these metallic glasses. The reason behind this failure is very obvious. In $Fe_{80}B_{20}$, the scanning electron-microscope studies show[22] that the domains ($\sim$600 μm in width) lie parallel to the ribbon axis with the magnetization oriented at 20°$\sim$30° off the ribbon axis in the plane of the sample. Due to the typical shape of these samples (thin, long ribbons), measurements of magnetoresistance and Hall effect are made in the orientation where the current flows parallel to the ribbon axis. It is clear from Sec. II D that when current flows parallel to the domain walls the Berger's mechanism[11] does not come into the picture. Hence, the normal ferromagnetic anisotropy of resistance is the only dominant mechanism for magnetoresistance as measured in the present orientation.

V. CONCLUSIONS

We conclude the following.

(i) We have found experimentally the concentration dependence of the absolute value of the room temperature resistivity ρ and verified theoretically for the first time the experimental trend.

(ii) The importance of correct sample alignment and the advantage of using one orientation ($\vec{H}\|$ ribbon plane) over the other ($\vec{H}\perp$ ribbon plane) when measuring the transverse magnetoresistance are pointed out.

(iii) The relation between the FAR and the saturation magnetic moment M_s (μ_B/Fe atom) for the series is established once again. A possible explanation is suggested for the sharpening of the peak in plots of the FAR versus x with decreasing temperature.

(iv) The concentration dependence of the spontaneous Hall constant R_s in this series is examined experimentally for the first time. A physical explanation is given for the occurrence of the peak in the R_s versus x plot.

(v) The lack of validity of the most commonly used correlation, $R_S=A\rho^n$, is pointed out for this series.

(vi) The usual ferromagnetic anisotropy of resistivity seems to be the dominant mechanism for magnetoresistance in this series.

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APPENDIX

In our earlier paper[1] we had calculated Θ_D assuming a T^2 dependence of resistivity (coming from electron-ion potential) in the temperature range $80 \leq T \leq 150$ K. In the process we had neglected the magnetic contribution which might contribute at low temperatures (e.g., $T < 100$ K). Nevertheless, in the case of $Fe_{80}B_{20}$ a detailed analysis of the resistivity data in the temperature range ($20 \leq T \leq 100$ K) was done to find out the magnon contribution to the resistivity. A least-squares fitting procedure was used for this purpose. The resistivity data were fitted to a power law of the form

$$\rho=a+bT^{3/2}+cT^2 .$$

The result of this fit (χ^2) shows that the data fit better to a single T^2 term than $T^{3/2}$ and T^2 terms together.

χ^2, b, c, when $T^{3/2}$ and T^2 terms are present		χ^2, c when only the T^2 term is present	
χ^2	1.24×10^{-9}	χ^2	3.21×10^{-9}
b	$-(0.15\pm0.02)\times10^{-5}$		
c	$+(7.24\pm0.23)\times10^{-7}$	c	$(5.81\pm0.04)\times10^{-7}$

In fact, if we consider the presence of both T^2 and $T^{3/2}$ terms the least-squares fitting gives an unphysical negative b as shown above.

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