Structural, magnetic, and electrical properties of (Pr0.5Er0.5)2Fe17−x Al x

K. G. Suresh and K. V. S. Rama Rao

Articles you may be interested in

Structural and magnetic properties of epitaxial Heusler alloy Fe2Cr0.5Co0.5Si
J. Appl. Phys. **115**, 17C301 (2014); 10.1063/1.4852117

The interface structure and magnetic and electronic properties of a Co2FeAl0.5Si0.5/MgO/Co2FeAl0.5Si0.5 magnetic tunneling junction
J. Appl. Phys. **109**, 083509 (2011); 10.1063/1.3567300

Soft magnetic properties of (Ni80Fe20)1−x(Ni0.5Zn0.5Fe2O4)x films for high frequency applications
J. Appl. Phys. **109**, 07A308 (2011); 10.1063/1.3535550

Structural and magnetic properties of (Sm , Pr) 3 (Fe 1 − x Al x) 27.5 Ti 1.5 [x = 0.1 , 0.2 , 0.3]
J. Appl. Phys. **97**, 10H105 (2005); 10.1063/1.1851880

Order-disordered structure and magnetic properties of Li 0.5 Fe 2.5 − x Rh x O 4
J. Appl. Phys. **97**, 10F102 (2005); 10.1063/1.1849553

Structural, magnetic, and electrical properties of $(Pr_{0.5}Er_{0.5})_2Fe_{17-x}Al_x$

K. G. Suresh and K. V. S. Rama Rao[a]

Magnetism and Magnetic Materials Laboratory, Department of Physics, Indian Institute of Technology, Madras 600 036, India

An x-ray diffraction study of $(Pr_{0.5}Er_{0.5})_2Fe_{17-x}Al_x$ ($0 \leq x \leq 10$) shows an expansion of its unit cell with x. The crystal structure changes from hexagonal Th_2Ni_{17} to rhombohedral Th_2Zn_{17} at $x=6$. The magnetic moment decreases by increasing the Al concentration. This effect may be due to the charge transfer from Al to the $3d$ band of Fe. The Curie temperatures are found to increase with Al up to $x=3$ and then decrease up to $x=10$, and the possible underpinning mechanisms are discussed. X-ray diffractograms of the magnetically aligned samples indicate that the easy magnetization directions of the samples with $x=1,2,3$, and 4 lie on a cone about the c axis. Electrical resistivity measurements show that the residual resistivity increases drastically with the Al concentration. The temperature coefficient of resistivity becomes almost zero for intermediate Al concentrations. © *1995 American Institute of Physics.* [S0021-8979(95)05524-3]

I. INTRODUCTION

Iron-rich rare-earth intermetallic compounds of the type RE_2Fe_{17} (RE=rare earth) have been drawing considerable attention owing to their applications in the field of high energy density permanent magnets.[1–3] The compounds in this series crystallize either in the rhombohedral Th_2Zn_{17} or in the hexagonal Th_2Ni_{17} structure according to whether the rare earth is lighter or heavier. It is of particular interest to note that the RE_2Fe_{17} compounds are the most iron rich among all the intermetallic compounds. Nevertheless, these compounds by themselves are not suitable candidates for permanent magnets because of their low anisotropy and low Curie temperatures (T_C). Interstitial modification of these compounds by carbon and nitrogen could, however, increase the anisotropy and the Curie temperature.[4,5]

The Fe sublattice imparts a major contribution to the total anisotropy in these compounds. While the Fe sublattice anisotropy is planar, the rare-earth sublattice anisotropy is axial in the case of Er, Sm, Tm, and Yb, whose α_J values are positive. The rare-earth sublattice anisotropy is rather small compared with the Fe sublattice anisotropy and therefore, the total anisotropy is planar. The rare-earth sublattice anisotropy in these compounds, however, could be enhanced by interstitial modification with carbon and nitrogen to such an extent that it can exceed the planar anisotropy of the Fe sublattice. This effect has been observed in Sm_2Fe_{17} at room temperature.[6] In Tm_2Fe_{17} and Er_2Fe_{17}, such an increase in rare-earth sublattice anisotropy is less than that in $Sm_2Fe_{17}N_x$ and therefore, the total anisotropy constant is positive at lower temperatures. At higher temperatures, the Fe sublattice anisotropy predominates and the total anisotropy constant changes sign, resulting in a spin reorientation transition. However, as Sm is very expensive, an intense search for compounds containing other rare earths is in progress. It is therefore worthwhile to investigate a pseudobinary compound in which the rare-earth sublattice anisotropy exceeds the Fe sublattice anisotropy.

Structural investigations carried out on several RE_2Fe_{17} compounds have shown that, in the hexagonal structure, there are two crystallographically inequivalent sites for the rare earth in the unit cell namely, $2b$ and $2d$. The direction of magnetization is either axial or planar, depending on the type of rare earth and on the site which it occupies. Hence the rare-earth sublattice anisotropy could be strengthened by a proper choice of rare earths, provided that there exists a preferential occupancy of the two sites, rendering the direction of magnetization axial at both sites.[7] With respect to the RE_2Co_{17} compounds containing Er and Pr, it has been shown[7] that such preferential occupancy exists and that the rare-earth sublattice anisotropy is strengthened. ^{166}Er Mössbauer studies carried out on these compounds have also confirmed this preferential occupancy.[8] A similar increase in the anisotropy field has also been reported[7] in $Tm_{2-x}Pr_xCo_{17}$. It is therefore reasonable to assume that such an increase in anisotropy occurs in the RE_2Fe_{17} compounds as well. The lattice parameter variations in $Er_{2-x}Pr_xCo_{17}$ have shown that the "a" values are more affected than the "c" values as x is increased.[7] This lends supportive evidence to the concept of preferential occupancy. This follows from the fact that the $2b$ site has close nearest-neighbor distances along the c axis and therefore, a Pr ion occupancy at that site would have caused a larger distortion of the c axis. Since such an effect is not observed in $Er_{2-x}Pr_xCo_{17}$, it indicates that the Pr ion occupies the $2d$ site.[7] Similar variations in the lattice parameters have also been observed[9] in $(Er_{1-x}Pr_x)_2Fe_{17}$. These probably suggest that Er and Pr ions occupy the $2b$ and the $2d$ sites, respectively, and that this could give rise to a net increase in the rare-earth sublattice anisotropy in $(Er_{1-x}Pr_x)_2Fe_{17}$. In addition, Pr, being a light rare earth, couples ferromagnetically with the Fe sublattice magnetic moment, thereby increasing the total magnetization. This, in turn, increases the theoretical energy product, an important parameter as far as a permanent magnet is concerned. It has been established[10] that Fe sublattice anisotropy could be reduced by replacing Fe with a nonmagnetic element like Al,

[a]Author to whom all correspondence should be addressed; Electronic mail: phy2@iitm.ernet.in

with a resultant increase in the total anisotropy. Several reports[11–13] indicate that Al can replace Fe in a very wide concentration range and that Al increases the Curie temperature considerably. Furthermore, very large values of magnetic hardness have been obtained at cryogenic temperatures, both in powder and bulk samples of $SmCo_5$, by substitution of Al for Co.[14] With the goal of identifying new compounds in this series based on the above-mentioned facts, we have selected a pseudobinary compound $(Pr_{0.5}Er_{0.5})_2Fe_{17}$ and studied the effect of Al substitution on its structural, magnetic, and electrical properties and the results are presented in this article.

II. EXPERIMENTAL DETAILS

Alloy buttons of all the compounds (x=0,1,2,3,4,5,6,8, and 10) were prepared by arc melting the constituent elements (Er and Pr of 99.9% purity and Fe and Al of 99.99% purity) in an argon atmosphere. The ingots were melted several times to ensure homogeneity. The as-cast samples were then wrapped in tantalum foil and annealed in vacuum for 7 days at 900 °C.

Powder x-ray diffractograms using Mo $K\alpha$ radiation showed that all the compounds have formed in single phase. The lattice parameters were evaluated by least-squares refinement. Magnetization measurements were carried out on magnetically nonaligned samples by means of a PAR 155 vibrating sample magnetometer in the temperature range of 77–600 K up to a maximum field of 1 T. Measurements at low temperatures were performed by continuous flow method using liquid nitrogen. An oven assembly was used for high-temperature measurements. The Curie temperatures of the compounds (up to x=6) were calculated from M^2-T plots at a low field of 0.5 kOe. For the compounds with x=8 and 10, the Curie temperatures were determined from the ac magnetic susceptibility measurements using a Sumitomo ac susceptometer.

The easy magnetization directions were identified from the x-ray diffractograms of the magnetically aligned samples. Aligning was done by mixing the samples with epoxy resin and allowing them to harden in a magnetic field of 1 T.

Electrical resistivity measurements were carried out using a four-probe technique. Samples in the form of discs (dimensions: 6 mm diam and 1 mm thickness) were cut from the annealed ingots using a diamond cutter and subsequently polished. These samples were then reannealed at 1000 K for 24 h. For low-temperature measurements, silver paint was used for making contacts. A constant current source delivering a current of 90 mA and a Keithley 181 nanovoltmeter were employed. A closed-cycle helium refrigerator was used to carry out the experiments in the temperature range of 16–300 K. The sample chamber was filled with helium gas. The temperature was monitored and controlled using a Leybold LTC 60 controller.[15] Pressure contacts were made for high-temperature experiments. At high temperatures also, the sample was kept in helium gas atmosphere. A resistance furnace was used to attain high temperatures and a chromel–alumel thermocouple was employed as the sensor to measure the temperature.
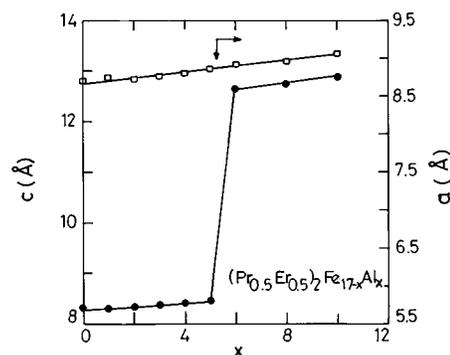

FIG. 1. Variations of "a" and "c" lattice parameters with Al concentration in $(Pr_{0.5}Er_{0.5})_2Fe_{17-x}Al_x$.

III. RESULTS AND DISCUSSION

The powder x-ray diffractograms show that the compounds with $x \leqslant 5$ possess the Th_2Ni_{17}-type hexagonal structure, whereas those with $x \geqslant 6$ possess the Th_2Zn_{17}-type rhombohedral structure. Figures 1 and 2 show the variations in the lattice parameters and the unit cell volume, respectively, with Al concentration. Since the volume of the rhombohedral unit cell is 3/2 times larger than that of the hexagonal unit cell, we have multiplied the former by a factor of 2/3, so that both of them can be directly compared. It can be seen from Fig. 2 that there is an increase in the unit cell volume with Al concentration. The atomic radius of Al is larger than that of Fe and therefore, replacing Fe with Al would cause an increase in the lattice parameters. There are four crystallographically inequivalent sites for Fe in the unit cell. Neutron diffraction studies[16] recently carried out on the $Tb_2Fe_{17-x}Al_x$ compounds have shown that Al completely avoids the $9d$ site. In the Al concentration range of 0–6, Al favors the $18h$ site and occupies the $6c$ and $18f$ sites almost randomly. At higher concentrations, these trends change and Al highly favors the $6c$ and $18f$ sites. A similar site occupancy has also been reported[17,18] in the $Nd_2Fe_{17-x}Al_x$ compounds. In addition, these studies have shown that the Al substitution pattern is rather independent of the rare earth. There is a linear increase in the lattice parameters and the unit cell volume with Al concentration in these compounds. Similar variations have also been observed in
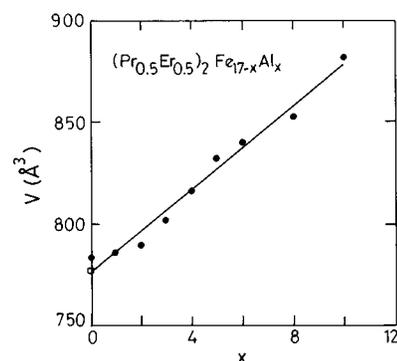

FIG. 2. Unit cell volume as a function of x in $(Pr_{0.5}Er_{0.5})_2Fe_{17-x}Al_x$.
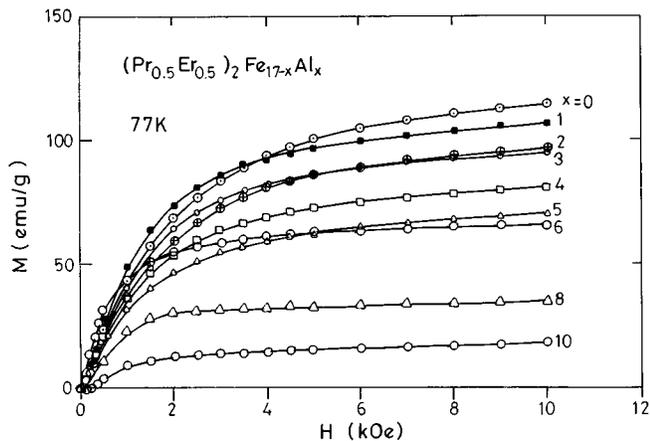
FIG. 3. Magnetization as a function of applied field for various values of x in $(Pr_{0.5}Er_{0.5})_2Fe_{17-x}Al_x$ at 77 K.

FIG. 5. Variation of the Curie temperature as a function of x in $(Pr_{0.5}Er_{0.5})_2Fe_{17-x}Al_x$.

$(Pr_{0.5}Er_{0.5})_2Fe_{17-x}Al_x$. Therefore, we can assume that the Al distribution pattern in this series of compounds is identical to those in $Nd_2Fe_{17-x}Al_x$ and $Tb_2Fe_{17-x}Al_x$.

Figure 3 shows the magnetization as a function of applied field for all samples at 77 K. There is a decrease in the magnetization with Al concentration. This could be explained on the basis of the band model, since the $3d$ electrons are itinerant in nature.[19] With the increase in Al concentration, there might be a charge transfer from Al to the $3d$ band of Fe. The spin-up and spin-down density of states are both unfilled for the parent compound. They get progressively filled up and the spin-up subband gets completely filled with the increase in Al concentration. Consequently, the magnetic moment of the $3d$ sublattice decreases, thereby decreasing the total magnetization. A similar reduction in the magnetic moment has also been observed[18,20] in other $RE_2Fe_{17-x}Al_x$ compounds.

The temperature variations of the magnetization, at a field of 1 T, for all samples are shown in Fig. 4. There is an increase in the Curie temperature from 285 to 435 K, as the Al concentration is increased from 0 to 3. At higher Al con-
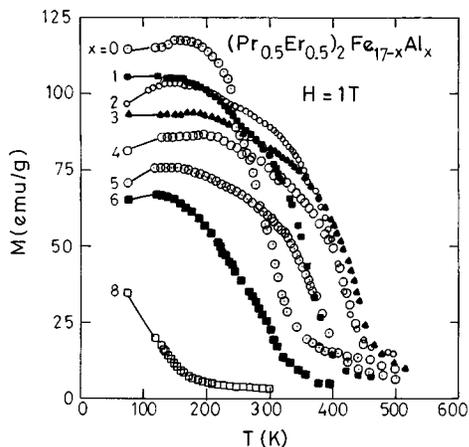

FIG. 4. Temperature variation of the magnetization for different values of x in $(Pr_{0.5}Er_{0.5})_2Fe_{17-x}Al_x$ at a field of 1 T.
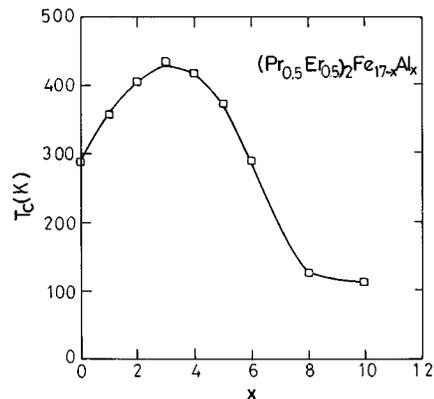
centrations, there is a monotonic decrease in the Curie temperatures. Figure 5 shows the variation in the Curie temperature with Al concentration.

The increase in the Curie temperature in the initial Al concentration range ($0 \leqslant x \leqslant 3$) could be attributed to the magnetovolume effect. RE_2Fe_{17} compounds have been found to exhibit anomalies in thermal expansion, forced volume magnetostriction, pressure dependence of Curie temperature, and magnetic moment. This is because of the presence of the magnetovolume effect in these compounds.[21] The magnetic state of a material exhibiting magnetovolume effect is dependent on its volume. The increase in the Curie temperatures with Al concentration, in the range $0 \leqslant x \leqslant 3$, is a consequence of the increase in the Fe–Fe distance due to lattice expansion.

In RE–transition metal (TM) intermetallic compounds, the Curie temperature is determined by the TM–TM and RE–TM exchange interactions. The strength of the RE–TM interaction in the case of different rare earths is proportional to their de Gennes factors, $(g-1)^2J(J+1)$. Since Gd has the highest de Gennes factor among all the rare earths, the RE–TM contribution to the Curie temperature would be a maximum for Gd_2Fe_{17}. The RE–TM exchange coupling constants (J_{RT}) derived from the analysis of the Mössbauer spectra of Dy_2Fe_{17} by Gubbens and Buschow[22] as well as from the inelastic neutron scattering experiments carried out on Ho_2Fe_{17} by Clausen et al.[23] have revealed a maximum contribution of 8 K to the Curie temperature of Gd_2Fe_{17}.[21] Since the present series of compounds contains Pr and Er, the RE–TM contribution would be less than 8 K, the reason being that the de Gennes factors of both Pr and Er are smaller than that of Gd. In $(Pr_{0.5}Er_{0.5})_2Fe_{17}$, therefore, the RE–TM contribution to the Curie temperature is negligible and the major contribution arises from the TM–TM exchange interaction. In the Al-substituted compounds of RE_2Fe_{17}, the RE–TM contribution remains unaltered on Al substitution, as shown by Jacobs et al.,[24] who have calculated the RE–Fe exchange coupling constants (J_{RT}) by mean-field analysis. Therefore, it could be assumed that the main contribution to the Curie temperature in all compounds in the present series is due to the Fe–Fe exchange interaction. Dunlap et al.[25] also have reported that the Curie tem-

perature of the RE$_2$Fe$_{17}$ compounds is primarily dependent on the magnitude of J_{TT} and that both J_{RT} and J_{RR} are substantially smaller than J_{TT} and are relatively independent of interatomic distances. Jacobs *et al.*[24] have calculated the Fe–Fe exchange coupling constants of Y$_2$Fe$_{17-x}$Al$_x$ for different Al concentrations and have found that there is an increase in the $J_{\mathrm{Fe-Fe}}$ values with x, in the initial Al concentration range. It has also been shown by Jacobs *et al.* that $J_{\mathrm{Fe-Fe}}$ is almost independent of the rare earth.[24] These results further confirm our assumption that the increase in the Curie temperature of the (Pr$_{0.5}$Er$_{0.5}$)$_2$Fe$_{17-x}$Al$_x$ compounds with x, in the Al concentration range $0 \leqslant x \leqslant 3$, is due to the increase in the $J_{\mathrm{Fe-Fe}}$ values.

The maximum observed in the T_C vs x plot could be explained on the basis of the Friedel model of ferromagnetism.[26,27] According to this model, the interaction between two magnetic moments would be strong and ferromagnetic if the distance "d" between them is smaller than the distance "λ" covered by the main peak of the Friedel oscillations, i.e., if $\lambda/d > 1$. In $3d$ compounds, it has been established that the magnetic coupling is governed mainly by the nearest-neighbor interactions and that d is proportional to the lattice parameters. Similarly, it could be shown that λ is inversely proportional to the d band Fermi wave vector, k_F (i.e., $\lambda \sim 1/k_F$). For the $3d$ band in the RE$_2$Fe$_{17}$ compounds, k_F is large. Substitution of Al decreases the hole in the $3d$ band and hence, decreases k_F. This is further accompanied by lattice expansion, which increases the d values. Hence the ratio λ/d initially increases, leading to a more stable ferromagnetic phase, resulting in higher Curie temperature. At higher Al concentrations, λ/d decreases because of the large increase in the lattice parameters. This reduction, accompanied by the decrease in the magnetic moment of Fe, reduces the Curie temperature.

The powder x-ray diffractograms of the magnetically aligned samples can give information about the easy magnetization direction.[28–30] The fact that the easy magnetization direction lies in the basal plane could be understood from the strong $(hk0)$ reflections. In contrast, if it lies along the c axis, only (001) reflections would be intense. We have taken the x-ray diffractograms of the aligned samples with $x = 1, 2, 3$, and 4. Figure 6 shows the typical diffractogram of the aligned sample ($x = 3$) along with that of the nonaligned sample. Similar diffractograms are obtained for the samples with $x = 1, 2$, and 4 as well. Aligning could not be done for the sample with $x = 0$, since its Curie temperature is slightly lower than room temperature. From Fig. 6, it could be seen that there is a drastic increase in the intensity of the (004) reflection. However, there also exist strong $(hk0)$ reflections. In addition, we also observe mixed-index reflections like the (112) peak with significant intensities. These might suggest[29] that the easy magnetization direction lies on a cone about the c axis. Yang *et al.*[31] have reported that, in Er$_2$Fe$_{17}$, the easy magnetization direction lies in the basal plane in the whole temperature range up to the Curie temperature. The same behavior has also been reported in Pr$_2$Fe$_{17}$. However, in (Pr$_{0.5}$Er$_{0.5}$)$_2$Fe$_{17-x}$Al$_x$, the easy magnetization direction lies
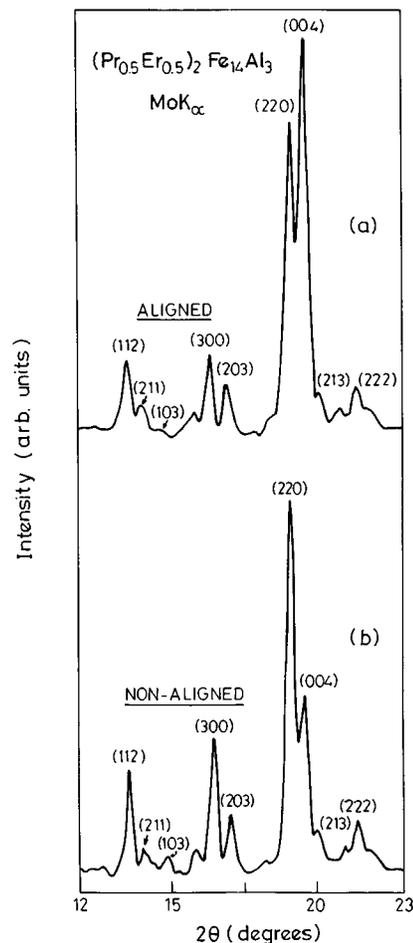

FIG. 6. Powder x-ray diffractograms of (a) magnetically aligned sample and (b) nonaligned sample with $x = 3$ in (Pr$_{0.5}$Er$_{0.5}$)$_2$Fe$_{17-x}$Al$_x$.

on a cone, implying that there is an increase in the total anisotropy. This may be due to the simultaneous increase in the rare-earth sublattice anisotropy on Pr substitution along with a reduction in the planar anisotropy of the Fe sublattice due to Al substitution. A similar increase in the anisotropy has also been reported[20] in Sm$_2$(Fe$_{1-x}$Co$_x$)$_{17-y}$Al$_y$.

Figure 7 shows the temperature dependence of the electrical resistivity (ρ) of all samples. All of them show metallic behavior in the temperature range investigated. It could be seen that there is an anomaly observed as a small change in the curvature of the ρ vs T plots at the Curie temperature, for the samples with $x = 0, 1, 2$, and 3. However, for higher Al concentrations, this anomaly is not observed. The absence of any pronounced anomaly at the Curie temperature might be due to the fact that the spin disorder resistivity does not decrease when the sample is cooled below its Curie temperature. A similar behavior has also been observed in the case of RE$_6$(Fe,Mn)$_{23}$ compounds.[32] These compounds are considered to possess complex magnetic structures and this could be the reason for such a behavior. This is in sharp contrast with the results of the resistivity studies carried out on Laves phase compounds, where a pronounced anomaly is obtained at the Curie temperature.[33–35] In the present case, there is a drastic increase in the resistivity with Al concentration. This
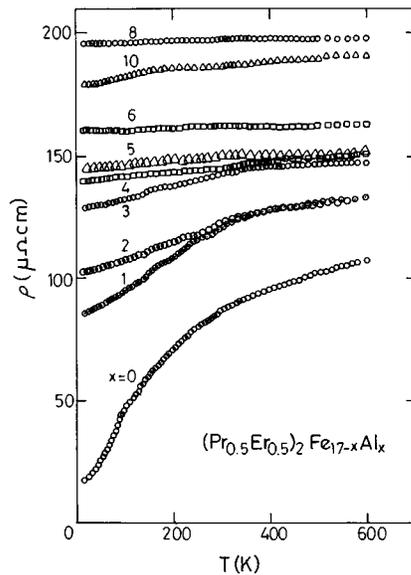
K. G. Suresh and K. V. S. Rama Rao

FIG. 7. Temperature dependence of the electrical resistivity for various values of x in $(Pr_{0.5}Er_{0.5})_2Fe_{17-x}Al_x$.

$\rho_{ph}(T)$ is due to the interaction of the conduction electrons with thermally excited phonons, while $\rho_{mag}(T)$ arises from the spin-dependent scattering processes. Since no pronounced anomaly is observed at the magnetic transition temperature in the $(Pr_{0.5}Er_{0.5})_2Fe_{17-x}Al_x$ compounds, it could be assumed that the magnetic contribution is fairly small compared with the phonon contribution. Hence the resistivity at 16 K could be taken as the residual resistivity. $\rho_{16\ K}$, therefore, represents the temperature-independent resistivity arising due to factors such as Coulomb scattering from substituted Al atoms, scattering from defects and dislocations, etc. Besides, a considerable change in the electronic structure might also be one of the reasons for the very large increase in the residual resistivity. A similar increase in the residual resistivity has also been observed[38] in the $RE(Fe_{1-x}Al_x)_2$ compounds.

ACKNOWLEDGMENT

is simultaneously accompanied by a reduction in the temperature coefficient of the resistivity, which becomes zero for intermediate Al concentrations. The most important contribution to the scattering of charge carriers appears to be from the random distribution of Fe and Al atoms possessing different scattering potentials. In addition, the presence of a large number of atoms in the unit cell could also be one of the reasons for this behavior.

The resistivity behavior in the present series of compounds could be explained by the Mooij rule.[36] The Mooij rule gives the correlation between resistivity and its temperature coefficient. According to this rule, the drastic increase in the resistivity in these types of compounds is caused by the considerable amount of scattering of the charge carriers due to the large extent of disorder mentioned above. In the case of alloys containing transition metals, the scattering is increased by the $s-d$ interaction. The electrical resistivity measurements carried out on several RE–TM intermetallic compounds have shown that the major contribution to the resistivity arises from the $s-d$ scattering owing to the very high density of states in the d band.[37]

The low value of the temperature coefficient of the resistivity could be a consequence of the fact that, as the Al concentration increases, the carrier mean free path reaches a lower limit. Such a limit is inevitable because the mean free path cannot be smaller than the interatomic distance, i.e., $kL \geqslant 1$ (k=wave vector and L=mean free path). When this limit is reached, a further decrease in mean free path due to phonons is not possible and practically all atoms behave as scattering centers, resulting in a low temperature coefficient of the resistivity.

The total resistivity for these compounds could be written as

$$\rho_{total} = \rho_0 + \rho_{ph}(T) + \rho_{mag}(T),$$

where, ρ_0 is the temperature-independent residual resistivity.

[1] K. H. J. Buschow, Rep. Prog. Phys. **40**, 1179 (1977).
[2] W. E. Wallace, Prog. Solid State Chem. **16**, 127 (1985).
[3] K. Kumar, J. Appl. Phys. **63**, R13 (1988).
[4] J. M. D. Coey and H. Sun, J. Magn. Magn. Mater. **87**, L251 (1990).
[5] K. H. J. Buschow, T. H. Jacobs, and W. Coene, IEEE Trans. Magn. **MAG-26**, 1364 (1990).
[6] X. C. Kou, R. Grössinger, T. H. Jacobs, and K. H. J. Buschow, Physica B **168**, 181 (1991).
[7] M. Merches, W. E. Wallace, and R. S. Craig, J. Magn. Magn. Mater. **24**, 97 (1981).
[8] W. E. Wallace, M. Merches, G. K. Shenoy, and P. J. Viccaro, J. Phys. Chem. Solids **43**, 55 (1982).
[9] K. G. Suresh and K. V. S. Rama Rao, IEEE Trans. Magn. (to be published).
[10] Z. Wang and R. A. Dunlap, J. Phys. Condens. Matter **5**, 2407 (1993).
[11] T. H. Jacobs, K. H. J. Buschow, G. F. Zhou, and F. R. de Boer, Physica B **179**, 177 (1992).
[12] F. M. Mulder, R. C. Thiel, T. H. Jacobs, and K. H. J. Buschow, J. Alloys Comp. **197**, 25 (1993).
[13] T. H. Jacobs, K. H. J. Buschow, G. F. Zhou, J. P. Liu, X. Li, and F. R. de Boer, J. Magn. Magn. Mater. **104**, 1275 (1992).
[14] H. Oesterreicher, Solid State Commun. **14**, 571 (1974).
[15] M. Senthil Kumar, K. V. Reddy, and K. V. Rama Rao (unpublished).
[16] G. K. Marasinghe, S. Mishra, O. A. Pringle, G. J. Long, Z. Hu, W. B. Yelon, F. Grandjean, D. P. Middleton, and K. H. J. Buschow, J. Appl. Phys. **76**, 6731 (1994).
[17] W. B. Yelon, H. Xie, G. J. Long, O. A. Pringle, F. Grandjean, and K. H. J. Buschow, J. Appl. Phys. **73**, 6029 (1993).
[18] G. J. Long, G. K. Marasinghe, S. Mishra, O. A. Pringle, Z. Hu, W. B. Yelon, D. P. Middleton, K. H. J. Buschow, and F. Grandjean, J. Appl. Phys. **76**, 5383 (1994).
[19] K. N. R. Taylor, Adv. Phys. **20**, 551 (1971).
[20] W. Jianmin, L. Feng, and L. C. Tai, J. Magn. Magn. Mater. **134**, 53 (1994).
[21] R. J. Radwanski, J. J. M. Franse, and K. Krop, Acta Phys. Polonica A **68**, 373 (1985).
[22] P. C. M. Gubbens and K. H. J. Buschow, J. Phys. F Met. Phys. **12**, 2715 (1982).
[23] K. N. Clausen and B. Lebech, J. Phys. C: Solid State Phys. **15**, 5095 (1982).
[24] T. H. Jacobs, K. H. J. Buschow, G. F. Zhou, X. Li, and F. R. de Boer, J. Magn. Magn. Mater. **116**, 220 (1992).
[25] R. A. Dunlap, Z. Wang, and M. Foldeaki, J. Appl. Phys. **76**, 6737 (1994).
[26] J. Friedel, G. Leman, and S. Olszewski, J. Appl. Phys. **32**, 325S (1961).

[27] K. H. J. Buschow, Phys. Status Solidi A **7**, 199 (1971).

[28] Z. Yiwei, L. Zhonghua, T. Ning, L. Xinwen, R. W. Zhao, and F. M. Yang, J. Magn. Magn. Mater. **139**, 11 (1995).

[29] M. Katter, J. Wecker, C. Kuhrt, and L. Schultz, J. Magn. Magn. Mater. **117**, 419 (1992).

[30] W. Z. Li, N. Tang, J. L. Wang, F. Yang, Y. Zeng, and F. R. de Boer, J. Magn. Magn. Mater. **140**, 985 (1995).

[31] F. M. Yang, N. Tang, J. L. Wang, X. P. Zhong, R. W. Zhao, and W. G. Lin, J. Appl. Phys. **75**, 6241 (1994).

[32] E. Gratz and H. R. Kirchmayr, J. Magn. Magn. Mater. **2**, 187 (1976).

[33] K. R. Dhilsha and K. V. S. Rama Rao, J. Appl. Phys. **68**, 259 (1990).

[34] K. R. Dhilsha and K. V. S. Rama Rao, J. Appl. Phys. **73**, 1380 (1993).

[35] M. Senthil Kumar, K. V. Reddy, and K. V. S. Rama Rao, J. Appl. Phys. **74**, 5112 (1993).

[36] J. H. Mooij, Phys. Status Solidi A **17**, 521 (1973).

[37] T. Kasuya, Prog. Theor. Phys. **16**, 1 (1956).

[38] V. Sima, R. Grössinger, V. Sechovsky, Z. Smetana, and H. Sassik, J. Phys. F. Met. Phys. **14**, 981 (1984).