Temperature dependence of the electrical resistivity of amorphous Co$_{80-x}$Er$_x$B$_{20}$ alloys

O. Touragha, M. Khatami, A. Menny, H. Lassri, K. Nouneh

Abstract

The temperature dependence of the electrical resistivity of amorphous Co$_{80-x}$Er$_x$B$_{20}$ alloys with $x = 0$, 3.9, 7.5 and 8.6 prepared by melt spinning in pure argon atmosphere was studied. All amorphous alloys investigated here are found to exhibit a resistivity minimum at low temperature. The electrical resistivity exhibits logarithmic temperature dependence below the temperature of resistivity minimum $T_{\text{min}}$. In addition, the resistivity shows quadratic temperature behavior in the interval $T_{\text{min}} < T < 77$ K. At high temperature, the electrical resistivity was discussed by the extended Ziman theory. For the whole series of alloys, the composition dependence of the temperature coefficient of electrical resistivity shows a change in structural short range occurring in the composition range 8–9 at%.

1. Introduction

A number of investigations on the electrical resistivity of amorphous alloys have been reported [1–3]. The electrical resistivity as a function of temperature remains a subject of much discussion. On the other hand, it is known that the substitution of certain early 3d transition metals in TM–M (TM = transition metal, M = metalloid) alloys changes drastically the resistivity behavior [4,5]. The resistivity minimum not only can occur in dilute magnetic impurity alloys, but also coexists with ferromagnetism. The temperature dependence of the resistivity of ferromagnetic amorphous alloys results from a number of scattering mechanisms. A Kondo-like resistivity minimum has been found in many amorphous alloys. The magnetic properties of these alloys have been reported earlier [6–8]. All the samples are ferrimagnetic in the studied temperature range. The smallest Curie temperature corresponds to $x = 8.6$ and is approximately 640 K [8].

In this article we discuss the temperature dependence of the resistivity of the amorphous Co$_{80-x}$Er$_x$B$_{20}$ ($0 \leq x \leq 8.6$) alloys (a TM–M alloy doped with rare-earth element Er) from 4.2 to 300 K.

2. Experimental

The ribbons of amorphous Co$_{80-x}$Er$_x$B$_{20}$ alloys having a thickness of 30 μm and width of about 2 mm were prepared by melt spinning in pure argon atmosphere. The amorphous structure was verified by X-ray diffraction. The chemical composition of the samples was determined by electron probe microanalysis. The electrical resistivity measurements were made by a four-probe method from 4.2 to 300 K. The temperature measurements were made by a Si diode Sensor and a lakeshore DRC-82C temperature controller. Current and voltage leads were attached to the sample using non-superconducting cadmium–zinc solder.

The values of resistivity at different temperatures have been normalized: the normalized resistivity is defined as follows: $r_n(T) = [R(T) - R(T_{\text{min}})]/R(T_{\text{min}})$, where $R(T)$ is the resistance at temperature $T$ and $T_{\text{min}}$ is the temperature at which minimum in resistivity occurs.
3. Results and discussion

The temperature dependence of the normalized resistivity $r_n$ versus temperature for all alloys exhibits minima at $T_{min}$. The resistivity minimum has been observed in these amorphous alloys, as can be clearly seen in Fig. 1. It is evident that as $x$ increases there is a significant change in the temperature dependence of resistivity. The temperature at which minimum in resistivity occurs, varies in the range 12–37 K as $x$ varies (Table 1). This change is much smaller, however, in comparison with the drastic changes observed in Cr-doped [4] and V-doped [5] TM–M alloys.

In order to bring out the functional dependence of $r_n$ on $T$, we have used the following equations for each sample:

$$r_n(T) = \frac{\Delta R}{R} = \frac{R(T) - R(T_{min})}{R(T_{min})} = a + b \ln T, \quad T < T_{min}, \quad \text{(1)}$$

$$r_n(T) = \frac{\Delta R}{R} = \frac{R(T) - R(T_{min})}{R(T_{min})} = a' + b'T^2, \quad T_{min} < T < 77 \text{ K}, \quad \text{(2)}$$

where $a$, $a'$, $b$, $b'$ are coefficients.

Least-square fits to the resistivity data based on Eqs. (1) and (2) in the specified temperature ranges give the values for the above coefficients listed in Table 1. The normalized resistivity data at the temperature below $T_{min}$ are shown in Fig. 1 as a function of $\ln T$. Fig. 2 shows $T^2$ fit in the temperature range between $T_{min}$ and about 77 K to the normalized resistivity. As can be seen in these figures, least-square fits to the resistivity data based on Eqs. (1) and (2) are quite satisfactory.

As Mizutani et al. [9] and Hasegawa and Dermon [10] show, the temperature dependence of the electrical resistivity for amorphous Co$_{80-x}$Er$_x$B$_{20}$ ($0 \leq x \leq 8.6$) alloys can be fitted in the neighborhood of the resistivity minimum, to the following equation:

$$r_n = a_0 + b \ln T + b'T^2, \quad \text{(3)}$$

From Eq. (3), $T_{min}$ is given as

$$T_{min} = \left(\frac{-b}{2b'}\right)^{1/2}. \quad \text{(4)}$$

The values of $T_{min}$ calculated by Eq. (4) using experimental values of $b$ and $b'$ are found to be roughly in agreement with the observed values $T_{min}$, as shown in Table 1. The origin of the logarithmic temperature dependence of resistivity and the formation of the resistivity minimum in ferromagnetic amorphous alloys have been discussed in analogy with the Kondo effect in magnetically dilute alloys.

In the temperature range above $T_{min}$, [11] $r_n(T)$ comprises two positive contributions in amorphous ferromagnets: one varying as $T^2$ and the other $T^{3/2}$. The contribution of $T^{3/2}$ is greater than $T^2$. However, Kaul et al. [12], in a detailed analysis, discovered $T^2$ dependence

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**Table 1**

Some parameter values of the resistivity for amorphous Co$_{80-x}$Er$_x$B$_{20}$ ($x = 0, 3.9, 7.5, 8.6$) alloys

<table>
<thead>
<tr>
<th>Samples</th>
<th>$T_{min}^{exp}$ (K)</th>
<th>$T_{min}^{cal}$ (K)</th>
<th>$b \times 10^4$</th>
<th>$b' \times 10^2$ (K$^{-2}$)</th>
<th>$x \times 10^4$ (K$^{-1}$)</th>
<th>$\theta_{15}$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co$<em>{80}$B$</em>{20}$</td>
<td>18.2</td>
<td>20.16</td>
<td>-12.2</td>
<td>1.5</td>
<td>3.60</td>
<td>378 ± 33</td>
</tr>
<tr>
<td>Co$_{76}$Er$<em>3$B$</em>{20}$</td>
<td>17.5</td>
<td>23.6</td>
<td>-14.5</td>
<td>1.3</td>
<td>1.60</td>
<td>330 ± 31</td>
</tr>
<tr>
<td>Co$_{72}$Er$<em>5$B$</em>{20}$</td>
<td>36.5</td>
<td>41.3</td>
<td>-18.1</td>
<td>0.54</td>
<td>0.65</td>
<td>356 ± 43</td>
</tr>
<tr>
<td>Co$_{71}$Er$<em>8$B$</em>{20}$</td>
<td>12</td>
<td>15.8</td>
<td>-15.05</td>
<td>3</td>
<td>-0.1</td>
<td>332 ± 30</td>
</tr>
</tbody>
</table>
of resistivity in the intermediate temperature range in amorphous Fe$_{80}$B$_{20-x}$C$_x$ ($0 < x < 10$) alloys. They have suggested the quadratic temperature dependence of resistivity in the intermediate temperature range mainly originated from the scattering of the conduction electrons by the structural disorder and have claimed that the contribution to this $T^2$ term from coherent electron-magnon scattering was relatively small. We have also obtained a better $T^2$ fit in the intermediate temperature ranges depending on the composition samples, as it is shown in Fig. 2.

It is very interesting that the resistance minimum coexists with strong ferromagnetism in amorphous Co$_{80}$B$_{20}$ alloys doped with Er. This implies that there is the possibility of the existence of weakly coupled d spins in a strong ferromagnetically ordered material owing to the distribution of exchange integral in amorphous alloys. These weakly coupled d spins have the capability of spin flipping and hence can bring about a Kondo-type resistance minimum and ferromagnetism. The average hyperfine field at the Co nucleus decreases with Er concentration correspondingly, the average moment of the Co atom decreases with increasing Er content. This implies that there is the possibility of the structural disorder and have claimed that the hyperfine field has a broad distribution, which supports the experimental result of the coexistence of resistivity minimum and ferromagnetism. The average hyperfine field at the Co nucleus decreases with increasing Er content correspondingly, the average moment of the Co atom decreases with Er concentration, which contributes to an enhancement of the exchange interaction $J_{s-d}$, so that the coefficient $b$ also increases with increasing Er content.

In the temperature range $T > T_{\text{min}}$, if one considers that amorphous alloys are frozen liquids, one can apply Ziman’s theory of liquid metals to understand the temperature dependence of electrical resistivity in many amorphous alloys. Using the concept of the above theory, various authors [14] had explained the temperature dependence of resistivity in many amorphous systems. Following Nagel [15], the temperature coefficient of the electrical resistivity of the amorphous metals is given by

$$\alpha = \left[ \frac{1}{R} \frac{\partial R}{\partial T} \right] = \frac{2[S(2k_F)]\partial W(T)}{S(2k_F)}$$

where $k_F$ is the Fermi wave vector, $S(2k_F)$ is the structure factor corresponding to $k = 2k_F$, and $W(T)$ is the Debye–Waller factor related to temperature. The asymptotic temperature dependence of $W(T)$ in the Debye approximation is given by

$$W(T) = W(0) + 4W(0) \frac{\pi^2}{6} \left( \frac{T}{\theta_D} \right)^2, \quad T \ll \theta_D, \quad (5)$$

$$W(T) = W(0) + 4W(0) \left( \frac{T}{\theta_D} \right), \quad T \gg \theta_D, \quad (6)$$

where

$$W(0) = \frac{3\hbar^2k^2}{8Mk_B\theta_D}, \quad (8)$$

where $M$ is the atomic weight, $k_B$ and $h$ have their usual meaning, and $\theta_D$ is the Debye temperature. Using Eqs. (5)–(7), $\theta_D$ is found to be

$$\theta_D = \frac{\pi^2 z}{6\beta}, \quad (9)$$

where

$$\beta = \frac{1}{R} \frac{\partial R}{\partial T^2} \quad \text{for} \quad T \ll \theta_D.$$
Finally, a comment is due on the applicability of Ziman’s theory in these amorphous alloys. From Eqs. (6) and (7), one can find that the temperature dependence of the resistivity is

\[ r_n(T) = a \frac{T^2}{\theta_D^2}, \quad T \ll \theta_D, \quad (10) \]

\[ r_n(T) = a \frac{T}{\theta_D}, \quad T \gg \theta_D, \quad (11) \]

where \( a \) is a constant, which is independent of temperature. It is found \( \theta_D \) is above room temperature and the resistivity has a \( T^2 \) dependence between \( T_{\text{min}} \) and 77 K for amorphous \( \text{Co}_{80-2x}\text{Er}_x\text{B}_{20} \) alloys. Therefore, fact that the experimental results are in agreement with Eqs. (10) and (11) clearly shows that the variation of \( r_n(T) \) with \( T \) should deviate from linearity for temperatures below \( \theta_D \). In contrast to this, we find that the \( r_n \) vs. \( T \) graph (see Fig. 3) is linear in the temperature range 130 < \( T \) < 300 K. Esposito et al. [19] had shown that in the strong scattering liquids (Fe, Co) the extended Ziman theory could only give a qualitative description of the resistivity as against the weak scattering cases (Ni, Cu) where one obtains a better quantitative estimate of resistivity. Thus the values of \( \alpha \) calculated here on the basis of the above theory should be taken as only order of magnitude estimates.

4. Conclusion

The electrical resistivity as a function of temperature has been measured for amorphous \( \text{Co}_{80-2x}\text{Er}_x\text{B}_{20} \) (0 < \( x \) < 8.6) alloys in the temperature range 4.2–300 K. All samples show a minimum at low temperature. On the other hand, at high temperatures, the temperature coefficient of resistivity decreases with \( x \) and eventually becomes negative for \( x = 8.6 \). The electrical resistivity exhibits a logarithmic temperature dependence at \( T < T_{\text{min}} \) and a \( T^2 \) dependence in the interval \( T_{\text{min}} < T < 77 \) K. The Debye temperature calculated from the temperature coefficient of electrical resistivity above \( T_{\text{min}} \) is found to be about 360 ± 30 K. The limitation of the applicability of Ziman’s theory to these amorphous alloys is also pointed out.

References