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RESISTANCE MINIMA IN AMORPHOUS MIXED MAGNETIC SYSTEM Fe–Mn–PBA1

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Résumé.- Des études de la résistivité d'un système amorphe Fe-Mn-PBA1 montrent un minimum de résistivité à des températures comprises entre 100 et 255 K. On trouve que \(\rho(T)\) dépend linéairement de \(\rho(T)\) aux températures inférieures à \(T_{\text{min}}\), ce qui donne pour la contribution dominante à \(\rho\) au-dessous de \(T_{\text{min}}\) une dépendance exponentielle en \(T\). Ceci est aussi observé dans plusieurs autres systèmes amorphes étudiés.

Abstract.- Resistivity studies on amorphous Fe-Mn-PBA1 system show \(\rho_{\text{min}}\) at temperatures in the range 100–255 K. It is found that \(\rho(T)\) depends linearly on \(\rho(T)\) below \(T_{\text{min}}\), thus giving a simple exponential \(T\)-dependence for the dominant contribution to \(\rho\) below \(T_{\text{min}}\). This behaviour is also observed in several other amorphous systems studied by us.

INTRODUCTION.- The coexistence of resistance minimum and ferromagnetism in a variety of amorphous materials has been a subject of considerable recent work. That this \(\rho_{\text{min}}\) is also observed in the non-magnetic state of similar systems suggests a possible common origin for the phenomenon. Several theoretical approaches like the modified Kondo mechanism/1/, structure dependent tunneling model/2/, and the diffraction model/3/ have been proposed to explain this phenomenon. In order to test the applicability of these models, we have carried out systematic electrical resistivity studies on amorphous \(T_{0.75}(\text{PBAl})_{0.25}\) with \(T = \text{Fe}, \text{Co}, \text{Ni}/4\), Mn and Cr. Here, we report what we believe is the only detailed \(\rho\) study on a mixed magnetic system \((\text{Fe}, \text{Mn})_{x}T_{0.75}(\text{PBAl})_{0.25}\) which exhibits a continuous change from ferro to antiferromagnetic ordering with increasing Mn concentrations/5/.

EXPERIMENTAL DETAILS.- Thin ribbons of the amorphous materials were prepared by the centrifugal spin quenched method/6/ at Bell labs. Typically, these ribbons are \(\approx 25 \mu\text{m}\) thick and 1 mm wide. The Mn-rich samples are very brittle. Electrical contacts were attached to the sample surface using silver-paste. The absolute value of \(\rho\) was measured with a standard 4-probe technique using a Guildline Comparator Bridge (9970). The relative error in the \(\rho\) measurement is \(\approx 10\) ppm. The temperature of the sample was determined to a relative precision of a few mK over most of the range studied using Pt (25–300 K) and Carbon resistor (< 25 K) thermometers.

RESULTS AND DISCUSSIONS.- The overall behaviour of \(\rho\) with temperature for all the alloys studied is typical of that observed for amorphous magnetic systems with a well defined minimum at \(T_{\text{min}}\). Since in this paper we will discuss only the \(\rho\) behaviour below \(T_{\text{min}}\) we present in figure 1 the overall variation of \(\Delta \rho = \{\rho - \rho_{\text{min}}\}/\rho_{\text{min}}\) with \(\ln T\) for the various concentrations studied.

It is striking to note that \(T_{\text{min}}\) for this system increases rapidly and smoothly from around 8 K for the Fe-rich sample to 119 K for \(x = 1\), with a maximum at around 218 K for \(x = 0.5\). This change is at least an order of magnitude higher than that observed in the (Fe,Ni,Co)–PBAl alloy systems. The magnitude of \(\Delta \rho\) is also seen to be larger in this system (by a factor of ten) than in the case of the Fe,Co...
Ni-containing amorphous alloys. In magnitude, \( \rho \) is greatly increased with the addition of Mn from \( \sim 160 \, \mu\Omega \cdot \text{cm} \) for \( x = 0 \) to \( \sim 350 \, \mu\Omega \cdot \text{cm} \) for \( x = 1 \) (for details see Table I).

### Table I

Some pertinent data observed for amorphous Fe-Mn-P-B-Al alloys.

<table>
<thead>
<tr>
<th>( Fe_{1-x}Mn_x )</th>
<th>( T_{\text{min}} )</th>
<th>( \rho )</th>
<th>( \rho_T )</th>
<th>( \rho_T/\rho_0 = A + B \times e^{-CT} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x )</td>
<td>( \times 10^3 )</td>
<td>( \times 10^3 )</td>
<td>( \times 10^3 )</td>
<td>( \times 10^4 )</td>
</tr>
<tr>
<td>1.0</td>
<td>119.2</td>
<td>456.48</td>
<td>379.41</td>
<td>0.336</td>
</tr>
<tr>
<td>0.8</td>
<td>204.4</td>
<td>206.99</td>
<td>220.42</td>
<td>0.380</td>
</tr>
<tr>
<td>0.5</td>
<td>216.3</td>
<td>212.67</td>
<td>226.52</td>
<td>0.263</td>
</tr>
<tr>
<td>0.3</td>
<td>212.4</td>
<td>203.86</td>
<td>212.67</td>
<td>0.164</td>
</tr>
<tr>
<td>0.1</td>
<td>111.4</td>
<td>165.78</td>
<td>165.78</td>
<td>0.046</td>
</tr>
<tr>
<td>0</td>
<td>7.0</td>
<td>161.00</td>
<td>161.00</td>
<td>0.015</td>
</tr>
</tbody>
</table>

Several approaches to fit our data below \( T_{\text{min}} \) in accordance with the expectations from current theories were made. Simple fits to power laws of polynomials in temperature were found to be very unsatisfactory. The expression \( \Delta p = A - B \ln(T^2 + \Delta^2) \), expected for the increase in \( \rho \) below the minimum on the basis of the tunneling model/2/, was indeed found to fit our data quite well but with non-random deviations clearly beyond the experimental accuracy. Moreover, the values obtained for \( \Delta \), the energy gap expected from this model, were typically orders of magnitude larger (\( > 10 \, K \)) than that predicted by the theory. In addition, the value of \( \Delta \) was found to be strongly dependent on the Mn concentration. Since, there is little atomic size difference between Fe and Mn, one would not expect such a concentration dependence for \( \Delta \). We conclude, therefore, that this mechanism is not primarily responsible for the low temperature increase in the resistivity found in these glasses.

We find that the temperature coefficient \( \alpha = \rho(T)/\rho(T_0) \) below \( T_{\text{min}} \) varies linearly with \( \rho(T) \) in all the alloys studied. The insert in figure 2 is a representative plot of such a relationship in the case of the alloy with 50% Mn conc. Recently, Mooij/7/ has pointed out that such a relationship between \( \alpha \) and \( \rho \) is a universal feature of highly concentrated disordered transition-metal alloys. This linear relationship would imply that the temperature dependence of \( \rho \) below \( T_{\text{min}} \) is given by an expression of the type, \( \rho = A + Be^{-CT} \) (1) where \( A \), \( B \) and \( C \) are positive constants. We thus have a simple exponential behavior of the resistivity. Such an expression is found to give an excellent fit to our data on all the alloys with rms values for the mean deviation per data point \( \sim 3 \times 10^{-4} \mu\Omega \cdot \text{cm} \), which is at the level of our experimental errors. Table I lists the values of the constants \( B \) and \( C \) obtained for the Fe-Mn-P-B system. The value of these constants vary smoothly with the concentration. We have also found that such an exponential fit is universally valid in several of the amorphous systems studied by us. It must be noted that this type of exponential relationship is rather unique.

It is tempting to suggest that this exponential behavior is determined by the T-dependence of the Debye-Waller factor. Since in these transition-metal alloy systems an additional positive quadratic temperature dependent term dominates at higher temperatures, the observed resistance minimum is thus a natural consequence. Undoubtedly, the resistance minimum phenomenon is in some way dependent on the temperature below which the dominant phonon-wavelength is larger than the electron-mean-free-path.

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