THE LOW-TEMPERATURE RESISTIVITY OF AMORPHOUS IRON-PHOSPHORUS ALLOYS

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This note reports the results of low-temperature resistivity measurements on a simple binary amorphous ferromagnet, Fe-P. Iron-phosphorus can be made amorphous over a much larger composition range (~ 14 to 26 at. %P) than the previously reported amorphous ferromagnetic systems [1, 2, 3], and several interesting compositional effects have been observed. The specimens are made by electrodeposition, and the plating variables are given in Table 1. The composition (± 1 at. %) was determined by wet-chemical analysis. The structure, density, Curie temperature, and Mössbauer spectra of these alloys are described elsewhere.[4, 5] The resistivity was measured by a four-probe method between 4.2° and 80° K. Several specimens were measured up to room temperature and appeared linear above 150° K. Figure 1 displays data typical of all the specimens. The data was fit with an equation of the form, $\rho = \rho_0 + a \ln T + bT^2$, where a normalization term of the form, $-a \ln T_0$, is included in ρ_0 . A non-linear least-squares computer program yields the results in Table 2.

TABLE 1. PLATING VARIABLES

		g/liter of H ₂ O	
FeSO ₄ · 7H ₂ O	70-450		current 10-20 A/dm ²
NaH ₂ PO ₂ · H ₂ O	8-20		temp. 40-60°C
NH ₄ F	5		bagged iron anode
H ₂ SO ₄	add until pH 1.5-1.9		vigorous stirring

Figure 1. Temperature dependence of the resistivity.

TABLE 2. RESULTS OF COMPUTER FITTING

at. % P	Annealed at ($^{\circ}$ K)	ρ_o ($\mu\Omega\text{cm}$)	$a \times 10^2$ ($\mu\Omega\text{cm}$)	$b \times 10^4$ ($\mu\Omega\text{cm}/^{\circ}\text{K}^2$)	T_m ($^{\circ}\text{K}$)
	-	139.4104	- 8.01	4.48	9.5
14.3	376	139.4989	-13.09	4.27	12.4
	576	139.0357	-20.35	4.66	14.8
14.5	-	133.5570	- 8.68	2.80	12.5
	-	130.7396	- 6.28	1.36	15.2
15.9	376	130.6234	-11.24	1.51	19.3
	576	127.7588	-20.60	2.20	21.6
16.0	-	133.4807	- 9.93	1.74	16.9
18.0	-	144.4628	- 8.02	0.861	21.6
18.4	-	157.5171	-12.59	2.44	16.1
19.4	-	158.9892	-34.17	7.89	14.7
21.6	-	173.0051	-116.10	45.34	11.3

The error in ρ_0 may be as large as 15%, and is inherent in measuring the size of the small specimens. The major uncertainty in "a" and "b" comes from the error in temperature measurement and is estimated to be $< 10\%$. As an indication of how well the data is fit, the error in the fitting parameters is $< 2\%$ when estimated from the difference between the observed and predicted data points. The minimum in the resistivity is computed from $T_m = \sqrt{-a/2b}$.

Annealing experiments were done on two specimens at 373° and 573°K . The specimens crystallize at $\sim 686^\circ\text{K}$ (in vacuum). After each anneal, the minimum becomes deeper ("a" becomes more negative) and T_m increases. This suggests a relaxation to a more stable glassy structure.

Regarding the composition dependence of the fitting parameters, Figure 2 shows the minimum that occurs in b at $\sim 17.5\%\text{P}$. This coincides with the eutectic minimum of Fe-P. Although not so well-defined, a minimum in ρ_0 and a maximum in T_m also occur close to $17.5\%\text{P}$. A similar minimum is observed in the isomer shift for amorphous Fe-P alloys.[5]

While the logarithmic term has been attributed to electron-magnon scattering [6,7], the T^2 term could arise from either s-d scattering or spin-wave scattering.[8] The existence of a minimum in ρ_0 and b seems to favor s-d scattering since the filling of a split d-band with increasing phosphorus concentration could explain both minima.[8, 9, 10] Of course, this explanation hinges on precise knowledge of the density of states and the position of the Fermi level.

We are unaware of any model that might account for the position of the stationary points at the eutectic composition. The significance of

Figure 2. Composition dependence of the T^2 term.

the eutectic point may arise from a particular short-range order that occurs at that composition.[5] This is not unexpected in light of the mean free path (1-2 near-neighbor spacings), which suggests that the resistivity may be strongly influenced by the compositional or configurational short-range order. While the importance of a deep eutectic minimum for glass formation is well-known, it has received little theoretical attention since first being proposed.[11]

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