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Electrical resistance and crystallization characteristics of $Fe_{80}B_{20}$ [a)]

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The electrical resistance of amorphous $Fe_{80}B_{20}$ has been measured as a function of time at various temperatures during an isothermal crystallization process. The results fit a universal curve when $\Delta R/\Delta R_I$ is plotted against t/t_I. The value of t_I as a function of annealing temperature fits the Johnson-Mehl-Avrami equation with $n = 3$ changing to 1.4 for $t/t_I > 1.4$. The resistance of a series of partially crystallized samples was measured between 4.2 and 300 K. dR/dT at 300 K and dR/dlogT below the resistance minimum were both found to be linear funtions of $\Delta R/\Delta R_I$. That is, both the above quantities were found to be strictly proportional to the amount of crystalline phase present. This may pose some difficulty for the structural tunneling model of the low temperature resistance minimum in metallic glasses.

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INTRODUCTION

While many studies on the crystallization of amorphous metals exist (1), the influence of the crystallization process on electron transport in these materials is less well known. Accordingly we are studying the effects of crystallization on the electrical resistivity and thermoelectric power of these materials. We report here the initial work on the effect of the crystallization process on the resistivity of $Fe_{80}B_{20}$.

RESULTS

The samples of $Fe_{80}B_{20}$ were obtained from Allied Chemical Corp. as Metglas 2605 (2). The resistance measurements were made using a high sensitivity AC difference method similar to the one described by Muir and Ström-Olsen (3). Fig. 1 shows the electrical resistance measured as a function of time during an isothermal crystallization process for a number of different annealing temperatures. The data has been plotted on a reduced scale obtained by dividing the observed change in resistance ΔR by the change in resistance at the inflection point ΔR_I against t/t_I where t_I is the time at the inflection point. If we assume that the crystallized fraction is proportional to $\Delta R/\Delta R_I$ (4) and that complete crystallization has taken place at $t/t_I = 4$ where $\Delta R/\Delta R_I = -2.36$ then the transformed fraction, ξ, is given by $\xi = (\Delta R/\Delta R_I)/-2.36$.

The Johnson-Mehl-Avrami expression (5) for the transformed fraction in a nucleation and growth process is

$$\xi = 1 - e^{-kt^n} \qquad (1)$$

The inset of figure 1 shows a plot of $\ell n\ \ell n^1/(1-\xi)$ against $\ell n\ t/t_I$. A distinct change in n from 3.0 to 1.4 occurs at $t/t_I = 1.4$. Table I, after Christian (5), shows the expected value of n for various growth conditions. At the risk of over interpreting our data, it would seem that for our two dimensional ribbons we start with a constant nucleation rate (n=3) which tends towards saturation (n=2) at the same time that the diameter of the crystallized grains is approaching the width of the ribbon. We are thus tending towards one dimensional growth with a saturated nucleation rate which gives n=1.

Table I. Value of n for various growth conditions D=1,2,3 stands for 1,2 and 3 dimensional growth.

Nucleation rate	value of n		
	D=1	D=2	D=3
Increasing	>2	>3	>4
Constant	2	3	4
Decreasing	1-2	2-3	3-4
Zero (saturation)	1	2	3

Although probably not strictly correct (5) many workers have assumed an Arrhenius type activation behaviour for $d\xi/dt$.

The time to the inflection point, or any other fixed amount of transformation, is then given by

$$\ell n\ t_I = A + \Delta E/k_B T \qquad (2)$$

where the activation energy for the process E can be found from a plot of $\ell n\ t_I$ against 1/T. The present results give $\Delta E = 2.6$ eV which compares favorably to the reported values of 2.1 eV (6) and 2.5 eV (7).

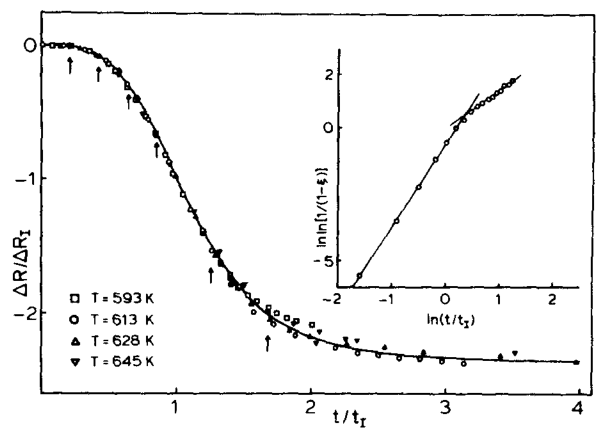

Fig.1. *Change in resistivity during crystallization.* The inset shows $\ell n\ \ell n[1/(1-\xi)]$ vs. $\ell n\ t/t_I$. The change in n from 3.0 to 1.4 at $t/t_I = 1.4$ is evident.

In order to examine the effects of partial crystallization on the temperature dependence of the resistivity six samples were annealed as indicated by the arrows in Fig. 1. Fig. 2 shows the resistance of these samples normalized to the resistance of the unannealed sample at 300 K. Fig. 3b shows dR/dT at 300K and dR/dlogT at 4.2 K plotted as a function of $\Delta R/\Delta R_I$. Within experimental error a good linear relation is obtained between these quantities and $\Delta R/\Delta R_I$ and if we assume that the effect on the resistivity of a composite material enters into dR/dT, dR/dlogT and $\Delta R/\Delta R_I$ in the same way (4) then a linear relation exists between dR/dT_{300K}, $dR/d\log T_{4.2K}$ and the degree of crystallization of the sample.

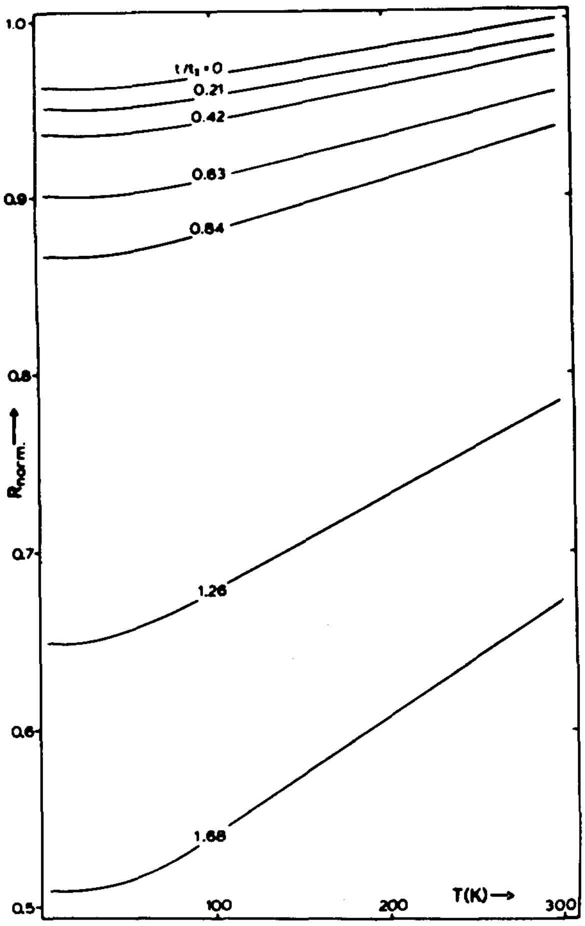

Fig.2. Normalized resistivity $R(T)/R_{300K}^{amorph}$ as a function of temperature for values of t/t_I corresponding to the arrows in Fig. 1.

The inevitable errors in the normalization procedure necessary to compare the resistance of various samples lead to large sample-to-sample errors at low temperatures and small degrees of crystallization. In order to avoid these errors an amorphous sample was measured and then annealed at 350°C for half an hour ($t/t_I \simeq 0.09$) and remeasured. The results are shown in Fig. 3a. There is no detectable difference in the low temperature results.

Recently Banville (8) has suggested that the density of tunneling states in an amorphous material should initially decrease on annealing. If this is true and the resistance minimum in $Fe_{80}B_{20}$ is due to the tunneling states as suggested by Cochrane (9), then an initial decrease in dR/dlogT on annealing would be expected. We see no such decrease. It can be concluded from this that (a) the tunneling model of the resistance minimum is not applicable; (b) the predicted decrease in tunneling states does not occur or (c) that the density of tunneling states responsible for the resistance minimum remains constant while an overall decrease in the density of tunneling states occurs but in an energy range which makes these states ineffective in the electrical conduction process.

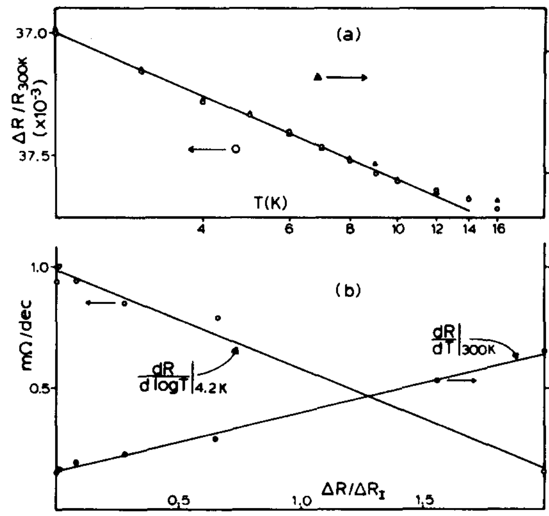

Fig. 3. a) $\Delta R/R_{300}$ as a function of T for an amorphous sample and for the same sample annealed to $t/t_I = 0.09$
b) $dR/dT|_{300}$ and $dR/d\log T|_{4.2}$ as a function of increasing crystallization ($\Delta R/\Delta R_I$).

CONCLUSIONS

The electrical resistance of $Fe_{80}B_{20}$ has been measured during isothermal crystallization. The results fit a universal curve over the temperature range 593 K to 645 K.

The shape of the curve fits the Johnson-Mehl-Avrami equation with the exponent n changing from 3 to 1.4 at $t/t_I = 1.4$ where the growth changes from two dimensional to one dimensional and the onset of saturation occurs in the nucleation rate. If an Arrhenius type mechanism is assumed, an activation energy of 2.6 eV is obtained for the annealing process.

The electrical resistance as a function of temperature was found to vary smoothly with the degree of crystallization.

$dR/dT_{300\ K}$ increased linearly with the degree of crystallization while $dR/d\log T_{4.2K}$ decreased linearly with crystallization. No change in the low temperature dR/dlogT could be detected at very short annealing times. This suggests either that the decrease in the density of tunneling states predicted by Banville (8) is not seen by the electrical resistance minimum in amorphous materials is not applicable to $Fe_{80}B_{20}$.

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b) Supported by CNPq, Brazil.
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4) The resistance of a composite material does not vary linearly with composition. However, if the differ-

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