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Low Temperature Hall-Effect Measurements in Some Metallic Glasses

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We report on simultaneous measurements of the Hall-effect and resistivity in the metallic glasses $Pd_{80}Si_{20}$ and $Ni_{78}Si_8B_{14}$. Data were taken within a temperature range of 1.7 to 300 K and in magnetic fields up to 1.1 T. Whereas the Hall constant is nearly independent of temperature in case of $Pd_{80}Si_{20}$, it changes sign at low temperatures in $Ni_{78}Si_8B_{14}$. The implications of the low temperature results are discussed with respect to the origin of a resistivity minimum, present in both alloys.

I. Introduction

There is continuing interest in the conduction mechanism of metallic glasses having resistivities in the range 80–150 μΩcm. Some of these alloys exhibit a positive temperature coefficient of the resistivity at high temperatures and a negative one at lower ones, thus showing a resistivity minimum. Among these are various FeB-alloys [1], $Ni_{78}Si_8B_{14}$ and $Pd_{80}Si_{20}$ [2, 3]. At room temperature the FeB-alloys show ferro- or paramagnetic and $Pd_{80}Si_{20}$ diamagnetic behaviour. In order to explain the resistivity minimum, it was demonstrated by Dierker et al. [2] and Kästner et al. [3] in case of $Pd_{80}Si_{20}$ that most of the increase of the resistivity at low temperatures is due to magnetic impurity-scattering. On the other hand there are proposals, relating the additional low temperature resistivity to correlation effects between the electrons [4], to scattering from inherent structural defects in the amorphous structure [5], to localization- and hopping-effects [6] or to a kind of modified Kondo-effect in a ferromagnetic matrix [7].

It is the aim of this paper to discuss the additional information obtainable from the Hall effect in this context. For this purpose Hall-effect and resistivity are determined simultaneously at the same sample as a function of temperature and magnetic field.

* This work is part of the Ph. D. thesis

II. Experimental Details

The resistivity measurements were performed with a standard four probe arrangement. The Hall-voltage is detected with the aid of a Galvanometer-amplifier, connected to an integrating microvoltmeter. A conventional *ESR* electromagnet provided the magnetic field B, calibrated by a NMR probe. The temperature is measured with a calibrated Carbon glass resistor, the accuracy is: ± 0.1 K. The whole system exhibits a noise voltage of less than 3 nV. The relative error of the resistance is about $2 \cdot 10^{-5}$, the precision of the Hall-resistivity better than 80 pΩcm. The main systematic error to the resistivity and to the absolute value of the Hall-constant R_H stems from a 5% uncertainty in the sample thickness. The amorphous alloys were prepared by the melt spin-techniques ($Ni_{78}Si_8B_{14}$ Vacuumschmelze Hanau) and by the splat cool-techniques ($Pd_{80}Si_{20}$, supplied by Prof. Güntherodt, Basel), respectively. Side arms for the pressure contacts were cut into the samples. Within the apparatus the specimen was varnished via an insulating substrate to a copper block in order to get good temperature homogeneity and stability. Typical sample dimensions were $10 \times 1 \times 0.04\,\text{mm}^3$. The amorphous state of the samples was checked by angle-dispersive x-ray diffraction.

III. Results and Discussion

The experimental results for the $Pd_{80}Si_{20}$ alloy are shown in Figs. 1 and 2. In order to document any possible correlation between resistance R and Hall-constant R_H both data sets are plotted together in Fig. 1. Each value for R_H is derived from the slope of a straight line, fitted to the $\rho_H(B)$ data given in Fig. 2. Since the $\rho_H(B)$ curves are straight lines the relation $\rho_H = R_H \cdot B$ can be applied. The Hall-constant R_H derived in this way turns out to be independent of temperature in the range 300 K down to 1.7 K. In Fig. 1 only data up to 40 K are given for clarity. The absolute value of the Hall constant, $R_H = -(6{,}7 \pm 0{,}3)\ 10^{-11}\,\text{m}^3\,\text{A}^{-1}\,\text{s}^{-1}$ compares well with the room temperature determination of Mizutani et al. [8]. These authors get for $Pd_{80}Si_{20}$:

$$R_H = -(7{,}2 \pm 1{,}0) \cdot 10^{-11}\,\text{m}^3\,\text{A}^{-1}\,\text{s}^{-1}.$$

A magnetoresistance could not be determined. Therefore, its relative contribution should be smaller than $4 \cdot 10^{-5}$ per Tesla. A naive interpretation of R_H according to

$$R_H = (ne)^{-1}, \tag{1}$$

where n describes the electronic number density and e is the electron-charge yields $z^* = 1.36 \pm 0.07$ for the number of electrons per atom. In this calculation a density $\rho_d = 10{,}3 \cdot 10^3\,\text{kgm}^{-3}$ [9] was used. However, this number is not very meaningful, since measurements of the electronic density of states [10] show no free electron-like behaviour. Hence, Eq. (1) should be replaced by [11]

$$R_H = \frac{3}{e N(E_F) \cdot m^* \cdot v_F^2}. \tag{2}$$

Here $N(E_F)$ denotes the density of states at the Fermi-level, m^* the tangential effective mass [12] and v_F the Fermi-velocity. In order to interpret the data according (2) numerical values of $N(E_F)$ and the energy-wave number characteristic $E(k)$ should be known.

From the constancy of R_H one can draw the following conclusions: *i)* there exists no thermal activation of charge carriers, since this would give $R_H \sim T$ [11], *ii)* no hopping mechanism is present, since such an effect would produce a temperature dependence of R_H via a T-dependence of the hopping integral J [11]:

$$R_H = (e \cdot N(E_F) \cdot J)^{-1}. \tag{3}$$

However, we cannot rule out a random phase description for the electron-system, since then $N(E_F) \approx n/J$ [13]. Thus, we should have also $R_H = \text{const.}$ in this case.

Magnetic impurities may produce a Kondo-effect in the resistivity. Since Kondo scattering yields an anisotropy in the relaxation time τ, R_H is very sensitive to this kind of impurities. As a consequence, the Hall resistivity ρ_H will show a nonlinear dependence on the magnetic field [14]. Since ρ_H/B of $Pd_{80}Si_{20}$ doesn't depend on the magnetic field B, as documented in Fig. 2, the concentration c of magnetic impurities should be very small. A rough estimate, using the error figure of $80\,\mu\Omega\text{cm}$ yields $c \lesssim 40$ ppm [14]. Our value of a relative resistivity change of $3 \cdot 10^{-4}$ at 1.7 K is compatible with this number [2].

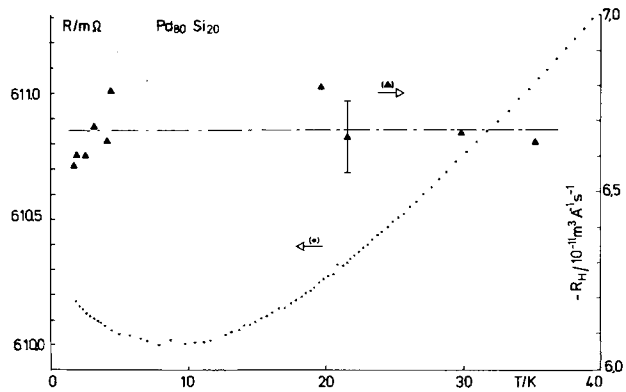

Fig. 1. Resistance R and Hall-constant R_H for amorphous $Pd_{80}Si_{20}$ in the temperature range 1.7 to 40 K and zero magnetic field. The chain line is a guide to the eye only

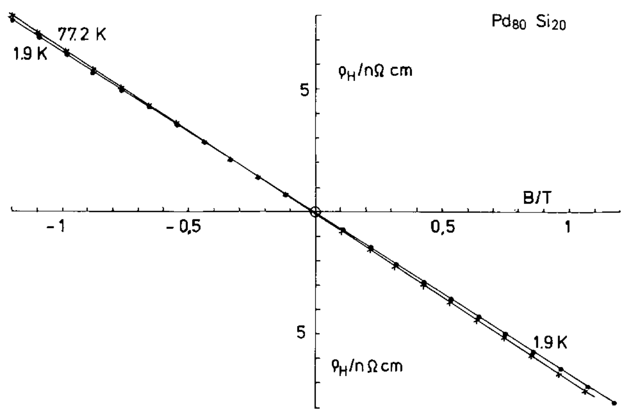

Fig. 2. Field dependence of the Hall-resistivity ρ_H at several temperatures for $Pd_{80}Si_{20}$. The full lines are least square fits

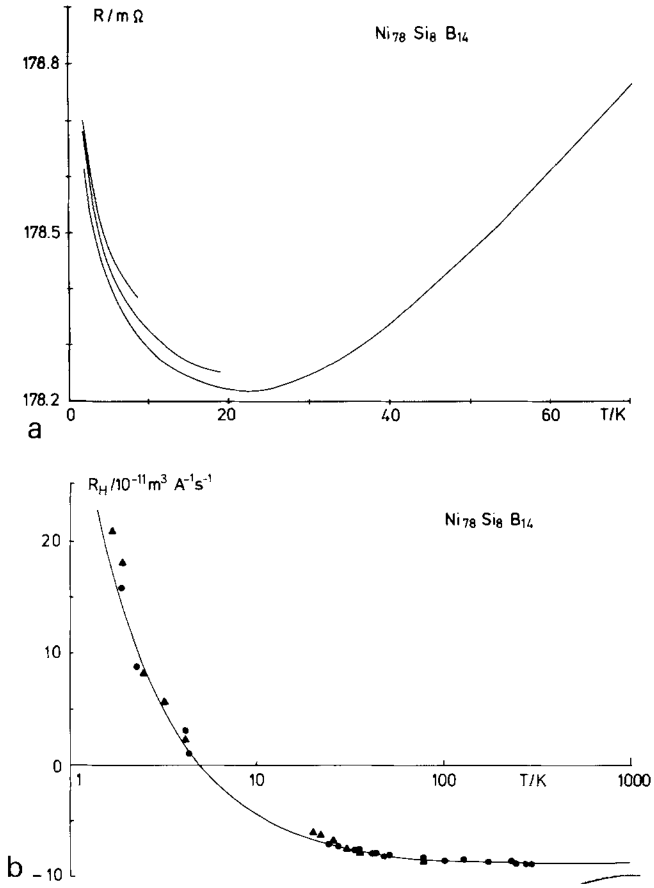

Fig. 3a. Resistance R for amorphous $Ni_{78}Si_8B_{14}$ in the temperature range 1.7 to 70 K. Several runs are shown for the low temperature part, they are shifted by constant amount for clarity. **b** The Hall-constant was derived from the initial slope of the ρ_H versus B curves (see Fig. 4). Data are given up to 300 K. The symbols refer to two different samples. The full line corresponds to a least square fit of a Curie-Weiss type behaviour to the data

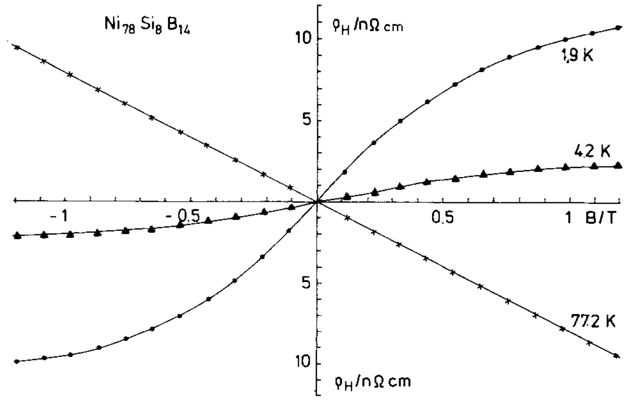

Fig. 4. Magnetic field dependence of the Hall-resistivity ρ_H for $Ni_{78}Si_8B_{14}$ for several temperatures. The full lines are guides to the eye only

The experimental data for $Ni_{78}Si_8B_{14}$ are reproduced in Figs. 3 and 4. The Hall constant R_H was determined from the $\rho_H(B)$ curves by using $R_H = \partial\rho_H/\partial B/_{B\to 0}$. It changes sign at about 9 K and starts to deviate from constancy at about 40 K, whereas the resistivity minimum shows up at 20 K. R_H approaches a constant negative value at higher temperatures of $R_H = (-8.8 \pm 0.4) \cdot 10^{-11}\,m^3A^{-1}s^{-1}$. This value compares well with the room temperature figure cited by Güntherodt et al. [15] of the alloy $Ni_{77}Si_{10}B_{13}$: $R_H = -8.72 \cdot 10^{-11}\,m^3A^{-1}s^{-1}$. The density was determined to be $\rho_D = 6.95 \cdot 10^3\,kgm^{-3}$. From these data we calculate the quantity $z^* = 0.84 \pm 0.06$.

Together with the field dependence of ρ_H (Fig. 4) which is nonlinear below 40 K, such a behaviour may be explained by the formation of ferromagnetic clusters at low temperatures. Skew- or side-jump-scattering of the electrons [16] contribute an additional R_{Ha} which adds to the usual negative free electron part R_{Ho}. In the paramagnetic state the temperature dependence of R_{Ha} should be determined by the one of the magnetic susceptibility χ [16]. Using a Curie-Weiss type behaviour for the latter, we write:

$$R_H = R_{Ho} + R_{Ha} = R_{Ho} + R_e\chi_0/(T - T_c), \tag{4}$$

where R_{Ho}, R_e and χ_0 are constants and T_c denotes the Curie-temperature. Using Eq. (4), we get a good fit to the data (Fig. 3b) with a $T_c \approx 0$ K. However, R_e cannot be determined, since the suceptibility constant χ_0 is not known.

The magnetoresistance is negative and small at high temperatures. However, at 1.9 K the relative change of the resistance turns out to be -10^{-4} when applying a magnetic field of B of 1 T. Its magnitude seems to depend quadratically on B.

The relative rise in the resistance with respect to its value at T_{min} amounts to about $4 \cdot 10^{-3}$. This large effect as compared to $Pd_{80}Si_{20}$ may still be related to a magnetic origin similar to the case of $Fe_{80}B_{20}$ or Metglas 2826 A [16]. Hence, we conclude that the scattering of the electrons from magnetic clusters is sufficient to produce the rise in the resistivity. Whereas in $Fe_{80}B_{20}$ $T_c \gg T_{min}$, in 2826 A $T_c \approx T_{min}$ [1], we have $T_c \lesssim T_{min}$ for $Ni_{78}Si_8B_{14}$. This situation may be caused by the relative magnitudes of the magnetic contributions at low temperatures with respect to the other ones, already present.

In conclusion we may state, that the rise in the resistivity at low temperatures can be explained by the Kondo-effect for $Pd_{80}Si_{20}$ and by strong magnetic scattering in case of $Ni_{78}Si_8B_{14}$, in analogy to the behaviour of the Fe-B-alloys.

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