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LETTER TO THE EDITOR

MAGNETORESISTIVITY OF TERNARY GLASSY $Zr_2(Ni_{1-x}M_x)_1$ ALLOYS

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We have measured magnetoresistivity of some ternary glassy $Zr_2(Ni_{1-x}M_x)_1$ alloys, M = Ti,V,Co and Cu, in magnetic fields up to 1.2 T at temperatures 4.2 K, 5 K, 6 K and 7 K. The magnetoresistivity of these alloys can be explained by adding contribution of the superconducting fluctuations to the contributions due to quantum coherence effects. The estimated values for inelastic relaxation times τ_i are very reasonable.

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In our previous investigations, electrical resistivity in the temperature range from 2 K to 300 K, superconducting transition temperatures and magnetic susceptibility of Zr-based glassy alloys were studied [1]. We investigated binary Zr-3d alloys $Zr_{1-x}Cu_x$ $(0.26 \leq x \leq 0.71)$, $Zr_{1-x}Ni_x$ $(0.22 \leq x \leq 0.67)$ and $Zr_{1-x}Co_x$ $(0.19 \leq x \leq 0.35)$. The measurements showed that electronic band structure at the Fermi level of these alloys is dominated by that of zirconium. The concentration dependence of the magnetic susceptibility, superconducting transition temperature and the electron-phonon interaction constant can all be explained in terms of the dilution of Zr by the 3d element. Recently, we extended our investigations to some ternary $Zr_2(Ni_{1-x}M_x)_1$ alloys (M = Ti, V, Cr, Mn, Fe, Co, Ni and Cu) [2–4]. The addition of a fixed amount of the third transition element M to the amorphous Zr_2Ni alloy causes a systematic decrease of the superconducting transition temperature T_c, of the density of states and the electron-phonon interaction constant when changing from Ti towards Cu. The pronounced minimum for M = Cr and Mn can be associated with the appearance of magnetic correlations [4,5]. Measurements of the magnetic susceptibility [6] also show a decrease when changing from Ti towards Cu, but with a maximum for M = Cr and Mn. Here, we report the preliminary results of our magnetoresistivity measurements for $Zr_2(Ni_{1-x}M_x)_1$ glassy alloys in low fields. In this work, we considered elements at the beginning and at the end of the 3d series of transition elements, i.e., for M = Ti, V, Co, Cu. We believe that measurements of the magnetoresistivity will give us a deeper insight into the electronic structure and especially the inelastic relaxation times τ_i of the alloys.

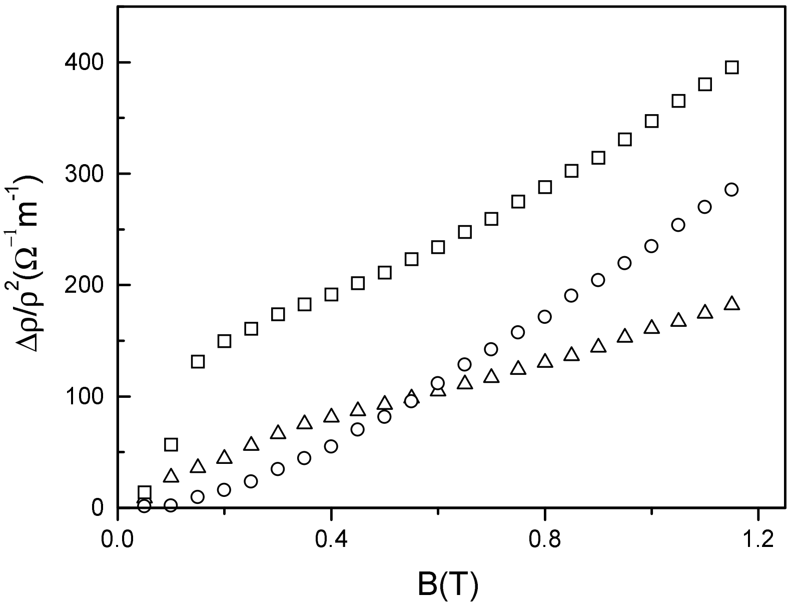

Fig. 1. Experimental magnetoresistance $\Delta\rho/\rho^2$ *vs.* B *of* $Zr_2(Ni_{0.9}Ti_{0.1})_1$ ($\bigcirc$), $Zr_2(Ni_{0.9}V_{0.1})_1$ ($\square$) *and* $Zr_2(Ni_{0.9}Cu_{0.1})_1$ ($\triangle$) *glassy alloys at 5* K.

The amorphous ternary Zr-3d alloys were prepared by melt spinning [7] from the master alloys with the predetermined concentration. The resulting ribbons were about 2 mm wide and 20-30 μm thick. The amorphous state of the alloys was verified by X-ray diffraction. Magnetoresistance measurements were carried out using an AC method, using 3–5 cm long samples supplied with thin Pt voltage and current leads, in magnetic fields $B \leq 1.2$ T provided by a superconducting magnet. The samples were mounted on a copper holder placed in a cryostat. The temperature range 3–10 K was covered using liquid-helium cooling and was controlled with germanium thermometer. The resolution of the magnetoresistance measurements was 1:10^6. The electrical resistivities were measured in the temperature range 8–300 K using a cryogenic refrigerator (RMC-Cryosystem LTS-22). The resolution in the resistivity measurements was 1:10^4. The superconducting transition temperatures of the alloys were determined by the induction method, with samples immersed in a liquid helium bath (pumped to the desired temperature).

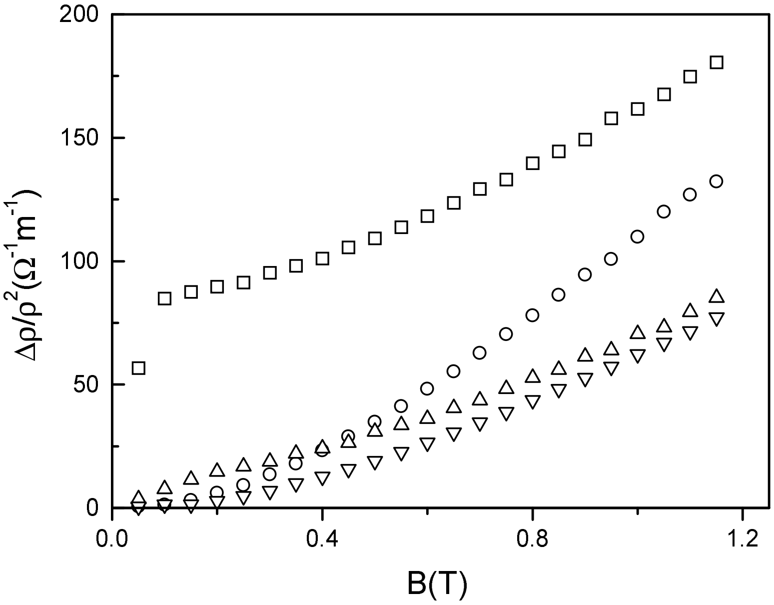

Fig. 2. Experimental magnetoresistance $\Delta\rho/\rho^2$ *vs.* B *of* $Zr_2(Ni_{0.9}Ti_{0.1})_1$ (○), $Zr_2(Ni_{0.9}V_{0.1})_1$ (□), $Zr_2(Ni_{0.9}Cu_{0.1})_1$ (△) *and* $Zr_2(Ni_{0.9}Co_{0.1})_1$ (▽) *glassy alloys at* 6 K.

In the previous work [2–4], we have shown that over a broad temperature range, variations of the conductivity with temperature in all these alloys can be qualitatively explained in terms of the incipient localization. It was found that the conductivity σ is proportional to T at lower temperatures ($T \leq \Theta_D/3$), and increases with $T^{1/2}$ at somewhat higher temperatures ($T \geq \Theta_D/3$). Inelastic relaxation time τ_i in non-magnetic disordered alloys is probably determined by the electron-phonon interaction [8]. At lower temperatures $\tau_i^{-1} \sim T^2$, and at higher temperatures $\tau_i^{-1} \sim T$. Figure 1 shows the measured magnetoresistance $\Delta\rho/\rho^2$ as a function of magnetic field for the alloys $Zr_2(Ni_{0.9}Ti_{0.1})_1$, $Zr_2(Ni_{0.9}V_{0.1})_1$ and $Zr_2(Ni_{0.9}Cu_{0.1})_1$ at 5 K. Figure 2 shows the measured magnetoresistance $\Delta\rho/\rho^2$ as a function of magnetic field for the alloys $Zr_2(Ni_{0.9}Ti_{0.1})_1$, $Zr_2(Ni_{0.9}V_{0.1})_1$, $Zr_2(Ni_{0.9}Co_{0.1})_1$ and $Zr_2(Ni_{0.9}Cu_{0.1})_1$ at 6 K. Previous analyses of the magnetoresistivity [9] for some superconducting alloys (among them $Zr_{43}Cu_{57}$) showed that the change of the magnetoresistivity with field can be explained by adding the contribution from superconducting fluctuations to the contributions due to quantum coherence effects. According to Altshuler et al. [10], the magnetoresistivity of a three-dimensional disordered metal with spin-orbit scattering is given by:

$$\frac{\Delta\rho}{\rho^2} = \alpha\frac{e^2}{2\pi^2\hbar}\left(\frac{eB}{\hbar}\right)^{1/2}\left[\left(\frac{1}{2}+\beta\right)f_3\left(\frac{B}{B_i}\right)-\frac{3}{2}f_3\left(\frac{B}{B_{so}}\right)\right] \qquad (1),$$

where β accounts for the quenching of the superconducting fluctuations,

$$B_i = \frac{\hbar}{4eD}\tau_i^{-1}, \qquad B_{so} = B_i + \frac{\hbar}{2eD}\tau_{so}^{-1},$$

D is the diffusion constant, τ_i^{-1} is the phase-breaking relaxation rate which is often identified with the inelastic relaxation rate, τ_{so}^{-1} is the relaxation rate for spin-orbit scattering and the factor α is equal 1 assuming theoretical results for free electrons. The function $f_3(x)$ can be expressed simply in two limits:

$$f_3(x) \approx \frac{x^{3/2}}{48} \qquad \text{for} \qquad x << 1 \tag{2}$$

$$f_3(x) \approx 0.605 \qquad \text{for} \qquad x >> 1 \tag{3}$$

When the spin-orbit scattering is stronger than the inelastic scattering ($B_{so} >> B_i$) magnetoresistivity is given by:

$$\frac{\Delta\rho}{\rho^2} = \alpha\left(\frac{1}{2}+\beta\right)\frac{e^2}{96\pi^2\hbar}\left(\frac{e}{\hbar}\right)^{1/2}\frac{B^2}{B_i^{3/2}} \qquad \text{for} \qquad B << B_i, \tag{4}$$

$$\frac{\Delta\rho}{\rho^2} = \alpha\left(\frac{1}{2}+\beta\right)\frac{0.605e^2}{2\pi^2\hbar}\left(\frac{eB}{\hbar}\right)^{1/2} \qquad \text{for} \qquad B << B_i << B_{so}. \tag{5}$$

For $B > B_{so}$, the magnetoresistivity becomes negative. β is the coefficient of the term of the superconducting fluctuations. It increases strongly when T approaches T_c. Figure 3 shows the measured magnetoresistance in a field of 1 T as a function of temperature. A rapid decrease of the magnetoresistivity with increasing temperature can be explained by a decrease in the coefficient $\beta(T, H)$. The relation between $\beta(T, H)$, the coupling constant g and temperature dependence of g was published by Larkin [11]. Generally, g is also a function of the magnetizing field and that dependence has been given by [12]:

$$g(T,H)^{-1} = \ln\frac{T_c}{T} + \Psi\left(\frac{1}{2}\right) - \Psi\left(\frac{1}{2}+\frac{DeH}{2\pi kT}\right), \tag{6}$$

where $\Psi(x)$ is the digamma function. It was computed using the following relation [13]:

$$\Psi\left(\frac{1}{2}\right) - \Psi\left(\frac{1}{2}+x\right) \approx -4x\left(\frac{1}{1+2x}+\frac{1}{9+6x}+\frac{85+32x}{150(5+2x)^2}\right) - \ln\left(1+\frac{2x}{5}\right). \tag{7}$$

Using relations (6) and (7), we calculated the constant $\beta(T,H)$, and from equation (4) B_i. D is calculated assuming the nearly free electron model:

$$D^{-1} = \rho e^2 N(E_F), \tag{8}$$

where ρ is the electrical resistivity and $N(E_F)$ is the density of states at the Fermi level. The factor α is determined from the slope of the linear variation with $B^{1/2}$, using relation (5). Experimental value of the factor α was between 0.5 and 1. To determine α more accurately, one must extend the measurements to higher fields.

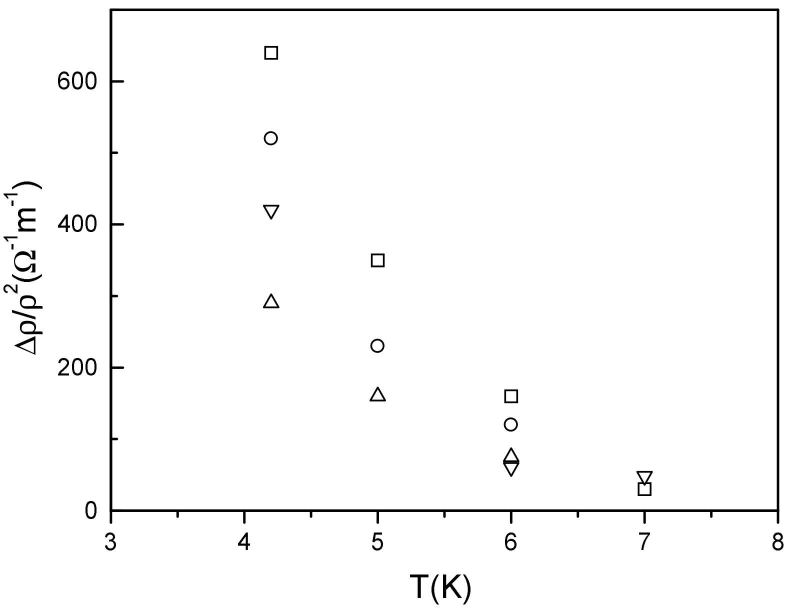

Fig. 3. Experimental magnetoresistance $\Delta\rho/\rho^2$ *versus* T *of* $Zr_2(Ni_{0.9}Ti_{0.1})_1$ (○), $Zr_2(Ni_{0.9}V_{0.1})_1$ (□), $Zr_2(Ni_{0.9}Cu_{0.1})_1$ (△) *and* $Zr_2(Ni_{0.9}Co_{0.1})_1$ (▽) *glassy alloys at* $B = 1$ T.

TABLE 1. $\rho_{4.2}$ *is the electrical resistivity at 4.2* K, T_c *is the superconducting transition temperature,* τ_{i1}, τ_{i2}, τ_{i3} *and* τ_{i4} *(in units of* 10^{-10} s*) are the electron inelastic relaxation times at 4.2, 5, 6 and 7* K, *respectively.*

M_x	$\rho_{4.2}(\mu\Omega\mathrm{cm})$	T_c(K)	τ_{i1}	τ_{i2}	τ_{i3}	τ_{i4}
$Ti_{0.1}$	174.1	2.99	0.35	0.23	0.16	
$V_{0.1}$	173.6	2.48	0.54	0.35	0.23	0.16
$Co_{0.1}$	181.0	2.76	0.32		0.13	
$Cu_{0.1}$	181.2	2.65	0.47	0.33	0.21	0.15

Since we were limited to 1.2 T, we introduced in relation (4) the theoretical value $\alpha = 1$. From B_i, we calculated the inelastic relaxation time τ_i. An analysis of the magnetoresistivity in Zr_2Ni [14] glassy alloys at 4.2 K yielded $B_i \approx 0.18$ T, $B_{so} \approx 5$ T and

$\tau_{so} \approx 2.44 \times 10^{-12}$ s. For our alloys, we supposed that $B_{so} >> B_i$, but for better accuracy we must take in account contribution to magnetoresistivity due to the spin-orbit interaction. To determine τ_{so}, we must measure magnetoresistivity in fields of about 5 T. In Table 1, we list some data and parameters obtained from the measurements: electrical resistivity at 4.2 K, superconducting transition temperature T_c and τ_i at temperatures 4.2 K, 5 K, 6 K and 7 K. Although superconducting fluctuations were predominant in the selected alloys, the calculated values of τ_i seem to be quite reasonable. In particular, our values of τ_i compare well with those obtained for similar amorphous Zr-based alloys [9,14]. As seen in Table 1, our data for τ_i do not show any systematic dependence on M. This may be expected concerning rather low content of M, and hence the dominant effect of Zr. We notice, however, some variation of τ_i with T_c, which may be associated with the uncertainty in the subtraction of $\beta(T, H)$. The coefficients $\beta(T, H)$ for our alloys were between 2.8 and 5 at 4.2 K, 1.8 and 2.7 at 5 K, 1.3 and 1.8 at 6 K and between 1.0 and 1.25 at 7 K. The change of β with magnetizing field was larger for lower temperatures, but when the field changed from 0 T to 0.3 T, the change of β was always less than 5%. The inelastic relaxation time is temperature dependent. That dependence can be written as $\tau_i^{-1} = CT^x$. For our measurements extending over a rather narrow temperature interval (and performed at four temperatures only), x was between 2 and 2.5. These values of x, although somewhat uncertain, are not inconsistent with those deduced for similar Zr-based alloys.

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MAGNETOOTPOR U TERNARNIM STAKLASTIM SLITINAMA $Zr_2(Ni_{1-x}M_x)_1$

Mjeren je magnetootpor nekih ternarnih staklastih slitina $Zr_2(Ni_{1-x}M_x)_1$, gdje je M = Ti, V, Co ili Cu, u magnetskom polju koje se mijenjalo od 0 T do 1.2 T, na temperaturama 4.2 K, 5 K, 6 K i 7 K. Pokazali smo da se magnetootpor tih slitina može objasniti dodavanjem doprinosa supravodljivih fluktuacija doprinosima koji nastaju uslijed kvantnih koherentnih efekata. Dobivene vrijednosti neelastičnih vremena raspršenja vrlo su prihvatljive.