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LETTER TO THE EDITOR

On the resistivity minimum in amorphous metallic alloys after plastic deformation or low-temperature annealing

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Abstract. The temperature at which minimum resistivity is observed in amorphous metallic alloys decreases on plastic deformation and increases on low-temperature annealing. These effects are explained in terms of the theory of electron transport.

The effect of plastic deformation on the low-temperature minimum in electrical resistivity $\rho(T)$ of a non-magnetic metallic glass has been investigated recently [1]. The minimum-resistivity temperature T_{min} was shown to decrease with increasing degree of deformation. For example, for the metallic glass $Ni_{78}Si_8B_{14}$ with $T_{min} \simeq 20$ K in the initial state (before deformation) it was found that the shift $\Delta T_{min} \simeq 5$ K at 6.1% roll reduction and $\Delta T_{min} \simeq 10$ K at 9.9% roll reduction.

Analysing the origin of the observed ΔT_{min}, the authors of [1] concluded that neither electron scattering in two-level systems [2] nor magnetic scattering [3] can be taken as a possible mechanism for the minimum-temperature shift of the resistivity, at least in non-magnetic metallic glasses. They used the mechanism of electron–electron interaction (EEI) [4] to explain the variations in $\rho(T)$. The contribution of the EEI to electrical resistivity is defined by the expression [4]

$$\delta\rho(T) \simeq -(T/\hbar D)^{1/2} \tag{1}$$

where $D = v_F \tau / 3$ is the diffusion coefficient for conduction electrons, v_F is the Fermi velocity and τ is the electron relaxation time.

The authors of [1] assumed that the shift of T_{min} is connected with an increase of the Fermi level and that any change in T_{min} would result in a change in D. The first effect is due to an increase of interatomic distance as a result of plastic deformation and thus to a decrease of the strength of the EEI term.

However, the diffusion coefficient D is determined in (1) by the impurity relaxation time of the electrons (without the EEI) [4]

$$\tau^{-1} = N_i g_i \pi \nu(\epsilon)$$

where N_i is the impurity concentration, g_i is the impurity potential intensity and $\nu(\epsilon)$ is the electron density of states without the EEI contribution.

Moreover, the effect of the EEI on $\nu(\epsilon, T)$ and $\rho(T)$ has been shown [4] to be different, so the minimum in $\rho(T)$ is not connected with the corresponding changes in the electron density of states. Hence the interpretation of the $T_{\min}$ shift as due to plastic deformation using (1) does not seem to be complete.

In our view this effect may be explained by the results of the theory of electron transport in amorphous metals and alloys [5]. In fact this theory [5] is the generalization of the EEI theory [4] for amorphous metallic alloys because it takes into account the influence of the eigenstructural state of these systems (dynamic short-range scattering), but not impurity scattering [4], on the EEI. In the impurity limit when the concentration C of one of the alloy components tends to 0, the theory [5] leads to the results of [4].

The contribution of the interference of the inelastic EEI and the dynamic short-range multiple elastic electron scattering to the resistivity [5] is

$$\delta\rho_{ee}(T) \simeq -(T/\hbar D)^{1/2}[1 + (T/T_0)^2]^{-1/4} \qquad (2)$$

where τ, included in D, is the electron relaxation time connected with the scattering of the dynamic concentration excitations (DCEs) corresponding to the eigenstructural state of amorphous alloys. Their detailed quantum-mechanical description is given in [6]. As is seen from (2), at $T \ll T_0$ it is similar to (1).

The characteristic temperature T_0 is of the order of a few kelvins [5–7] and is defined by the expression

$$T_0 = (2\pi)^3 \rho_0^2 \mu_0^{1/2} \omega_0 \hbar^3 / \kappa^3 C^2 (1 - C)^2 (\Delta E)^2 (2m)^{3/2} \qquad (3)$$

whre ρ_0 is the material density; $\kappa^2 = 4\pi e^2 \nu_0$ (ν_0 is the original density of states at the Fermi level); μ_0 is the electron chemical potential; and ΔE is the energy of formation of the cluster with the 'structure' k_s. Finally ω_0 is the boundary frequency determined by the half-width of the electron fluctuation states (FSS) [8], which are formed in the electron spectrum of amorphous metallic alloys similarly to the 'fluctuon' electron states in disordered semiconductors [9] due to the short-range order and the microscopic concentration fluctuations. ω_0 is of the order of 50 K [5–7].

It has been found [10] that the structure of deformed amorphous alloys is characterized by greater disordering within the sliding strips than in the structure of the initial materials. The data on the first maximum shift of the structural factor of deformed amorphous alloys in the small-angle range and the 'washing out' of this maximum [11] also testify to disordering in the sliding strips and the fracture of the short-range order of the initial composition with the formation of a smaller structure.

The formation of new non-characteristic types of short-range order should result in splitting of the FSS such that the energetic distances between the FSS and their half-widths would decrease. Consequently, plastic deformation should lead to the decrease of the boundary frequency of the DCEs and hence to the decrease of the characteristic temperature T_0 (see expression (3)).

It is obvious that the greater the degree of deformation the greater is this decrease. Thus in accordance with (2) the whole of the curve $\delta\rho_{ee}(T)$ with $T_{\min} \simeq 10 T_0$ [5] will be displaced to the left as a result of plastic deformation.

It is interesting to note that in the framework of this consideration the opposite situation, when $T_{\min}$ would be displaced to higher temperatures, could be explained. Let the amorphous alloy is put on the low-temperature annealing accompanied by the partial local atomic ordering of the type of structural relaxation mechanism [12]. In this case the

partial relaxation of the FSs (the consecutive transition from one FS to another as the direct transition of the FS to the crystalline phase band) results in the increase of the half-width of the non-relaxed FSs and the distances between them. Then the boundary frequency ω_0 of the DCES and the characteristic temperature T_0, and hence the temperature T_{min} of minimum resistivity, will increase. An increase in T_{min} as a result of low-temperature annealing has been actually observed [13].

Thus we assume that (2) allows us to give a more complete interpretation of the phenomena connected with plastic deformation [1] and low-temperature annealing [13] then the interpretation of [1].

In conclusion it should be pointed out that according to [6] and [7] the 'plateau' in the electron heat conductivity and the 'knee' in the thermopower at low temperatures, due to the same scattering processes as the resistivity minimum [5], will be displaced to the left after plastic deformation and to the right after low-temperature annealing.

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