Magnetoresistance of amorphous Cu-Ti alloys: The spin-orbit scattering time within weak localization

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(Received 27 February 1989)

The magnetoresistance of amorphous nonsuperconducting Cu-Ti alloys is analyzed with the weak-localization theory including spin-splitting and electron-electron interaction theories. The values of the spin-orbit scattering times $\tau_{s.o.}$ are found to be larger than values obtained from analyses neglecting the spin-splitting effect within weak localization or from the temperature dependence of the resistivity. $\tau_{s.o.}$ increases slowly with decreasing Cu content.

The magnetoresistance $\Delta\rho(B)$ of three-dimensional disordered alloys shows many interesting and complex features, which can be explained within the theories of weak localization and electron-electron interaction effects.[1,2] The studied systems cover by now a wide range of binary and ternary metallic glasses; such as Ca-Al-(Au),[3] Y-Al,[4] Mg-Cu-(Au), Mg-Zn-(Au),[5] Cu-Lu, Y-Si, Pd-Si,[6] Cu-Y,[6,7] Cu-Ti,[8] V-Si,[9] Lu-Ni, and Lu-Pd.[10] The theoretical contributions to $\Delta\rho$ give a rich variety of possible forms for the magnetoresistance as a function of temperature and magnetic field. $\Delta\rho$ can be either positive or negative. Theoretical expressions give $\Delta\rho\sim B^2$ in the low-field limit and for high fields, most of them give $\Delta\rho\sim\sqrt{B}$. These ranges are, however, individual for the different contributions. The dominating contribution at high temperatures ($T\leq 20$ K) comes from the weak-localization effect. At low temperatures ($T\approx 4$ K) the electron-electron effect due to Zeeman spin splitting in the particle-hole channel[11] $\Delta\rho_{p\text{-}h}$ is expected to become observable. The orbital contribution of the interaction effect in the particle-particle channel[12] $\Delta\rho_{p\text{-}p}$ will be important only at still lower temperatures ($T\leq 1$ K). In addition, superconducting materials also show a contribution from the quenching of superconducting fluctuations above the critical temperature.

Most of the interest in this field has been in extracting the inelastic scattering time τ_{ie} and the spin-orbit scattering time $\tau_{s.o.}$. These scattering times control the phase-breaking times which determine the sign and size of the weak-localization contribution[12] $\Delta\rho_{WL}$. This quantity is negative for $\tau_{s.o.}\gg\tau_{ie}$ and becomes positive when $\tau_{s.o.}\approx\tau_{ie}$. The inelastic scattering time is temperature dependent with $\tau_{ie}\sim T^{-p}$ if only one scattering mechanism dominates. Theoretically, p may take values from 1.5 for electron-electron scattering to 2–4 for electron-phonon scattering.[13] Values for p between 2 and 4 are commonly obtained from fits of the theoretical expressions to experimental data. There are several proposals for how $\tau_{s.o.}$ should be calculated,[6,14] which give different results. However, one should bear in mind that only electrons at the Fermi surface can scatter other electrons. Hence, $\tau_{s.o.}$ must be determined by the density of d states at the Fermi level times the spin-orbit coupling parameter. This latter quantity is modified with respect to the atomic value since the d electrons hybridize with the s electrons. Therefore, $\tau_{s.o.}\sim\langle z\rangle^{-q}$, where $\langle z\rangle$ is some average atomic number, seems not to be correct.

We will here give an analysis of the composition dependence of $\tau_{s.o.}$ for amorphous nonsuperconducting Cu-Ti alloys.[14] The Cu-Ti system is by far the best studied in terms of reports on localization and interaction effects in metallic glasses.[14–16] Nevertheless, we can give good reasons for yet another analysis of such effects in this system. Recently, it was pointed out[17] that the weak-localization effect including spin splitting[18] could account for the large magnitude of $\Delta\rho$ in Cu-Ti alloys. This was not the case, especially at low temperatures, when the

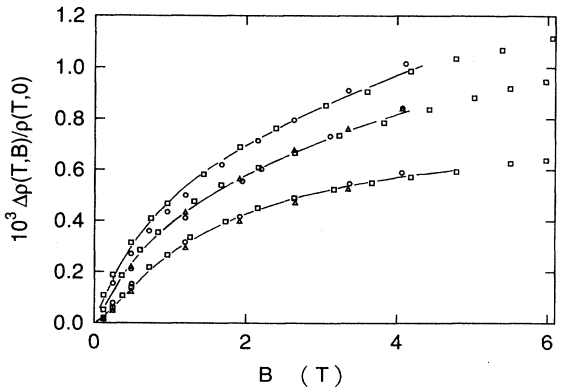

FIG. 1. The magnetoresistance for three samples and three temperatures vs magnetic field. The $\Delta\rho/\rho$ of the samples are almost identical at each temperature. From the top, the temperatures used were approximately 120 mK, 1.55 K, and 4.25 K. □, $Cu_{45}Ti_{55}$; △, $Cu_{60}Ti_{40}$; and ○, $Cu_{65}Ti_{35}$. The solid lines are only guides to the eye.

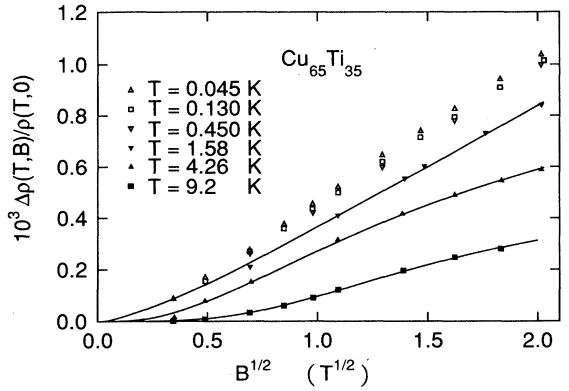

FIG. 2. The magnetoresistance vs square root of magnetic field. The data are $\sim\sqrt{B}$ at the lowest temperatures. The solid lines are fits to Eq. (1) as described in the text.

spin splitting was excluded. This approach is now used to determine the concentration dependence of $\tau_{s.o.}$ by a consistent analysis of a few Cu-Ti alloys.

The experimentally found magnetoresistivity $\Delta\rho$ is larger than expected in many amorphous systems. This has sometimes been solved by introducing an additional adjustable parameter in the localization expression[12] ($\Delta\rho^a_{WL}$) on an *ad hoc* basis. Fukuyama and Hoshino included the Zeeman spin splitting into this theory[18] ($\Delta\rho^b_{WL}$). The two expressions give almost identical results when the electronic diffusion constant $D>1$ cm^2/s as well as when $\tau_{s.o.}\to 0$ or ∞. In a range of values for $\tau_{s.o.}$, $\Delta\rho^b_{WL}$ is enhanced over $\Delta\rho^a_{WL}$, with $\Delta\rho^b_{WL}\sim D^{-1/2}$ and $\Delta\rho^a_{WL}$ independent of D. Many amorphous metals have D in the range 0.1–1.0 cm^2/s. The weak-localization expression $\Delta\rho^b_{WL}$ is thus necessary in the analyses of τ_{ie} and $\tau_{s.o.}$ in many metallic glasses. Excluding superconducting fluctuations, the total magnetoresistance is given by

$$\Delta\rho=\Delta\rho^b_{WL}(B,\rho,D,\tau_{ie},\tau_{s.o.})+\Delta\rho_{p\text{-}h}(B,\rho,D,T,\tilde{F}_\sigma)+\Delta\rho_{p\text{-}p}(B,\rho,D,T,g)\ . \quad (1)$$

ρ is the resistivity and T the temperature. $\tilde{F}_\sigma$ and g are the electron screening and electron-electron interaction parameters, respectively. $\Delta\rho_{p\text{-}h}$ is positive with $0\le\tilde{F}_\sigma\le 0.93$.[19] The sign of $\Delta\rho_{p\text{-}p}$ is determined by g, with positive $\Delta\rho_{p\text{-}p}$ for a negative g. An estimate for g gives $|g|<0.2$ (Ref. 12) for most metallic glasses.

TABLE I. Sample properties.

Sample	ρ(4.2 K) ($\mu\Omega$ cm)	D[a] (cm^2/s)	$\tilde{F}_\sigma$	$\tau_{s.o.}$ (ps)
$Cu_{45}Ti_{55}$	195±5	0.250	0.5	14.5
$Cu_{60}Ti_{40}$	187±5	0.285	0.6	11
$Cu_{65}Ti_{35}$	182±5	0.315	0.7	9

[a]The electronic diffusion constant D is calculated from specific-heat measurements (Ref. 21).

$\Delta\rho$ has been measured for $Cu_{45}Ti_{55}$, $Cu_{60}Ti_{40}$, and $Cu_{65}Ti_{35}$ between 45 mK and 9.2 K. The highest magnetic field used was about 6 T. The experimental method is described in Ref. 17. The three samples show almost identical $\Delta\rho$ as seen in Fig. 1. We fitted Eq. (1) with four adjustable parameters; τ_{ie}, $\tau_{s.o.}$, $\tilde{F}_\sigma$, and g. Series expansions[20] of the theoretical expressions for $\Delta\rho_{p\text{-}h}$ and $\Delta\rho_{p\text{-}p}$ were used. D was calculated from results of the electronic specific heat.[21]

We found it impossible to make an exact fitting to Eq. (1) if one demands a single parameter set, i.e., only τ_{ie} may have a temperature dependence. Starting at high temperatures it is possible to make good fits down to 1.5 K. $\Delta\rho_{p\text{-}h}$ accounts for about 10% of the total $\Delta\rho$, and $\Delta\rho_{p\text{-}p}$ is negligible at this temperature. We therefore excluded $\Delta\rho_{p\text{-}p}$ by setting $g=0$ and remade the fits for data above 1.5 K (Fig. 2). The results obtained are shown in Table I. $\tilde{F}_\sigma$ is here higher than the maximum value[17] of 0.4 as calculated from the temperature dependence of ρ. $\tau_{s.o.}$ increases with decreasing Cu content. The concentration dependence is weak, and is well described by a straight line. This is not obvious at all from Fig. 1. The analyses show that there are differences in curvature, which affect $\tau_{s.o.}$. One must remember that the fits are only made at two temperatures for two samples and for three temperatures for one sample ($Cu_{65}Ti_{35}$).

At low temperatures, the fitting procedures give a good picture of the complexity of the problems in this research area. On one hand, we have a theory with several adjustable parameters from which a large flexibility in form and temperature dependence of $\Delta\rho$ is possible. On the other hand, the experimental results show that these parameters cannot describe the phenomena on an absolute level at low temperatures. It should be mentioned in this context that we are talking about effects in the range of 10^{-4}. Small contributions from other sources, such as magnetic impurities, etc., may be present. In addition, all theories

TABLE II. $\tau_{s.o.}$ (ps).

Sample	Our results	Howson *et al.* (Ref. 16)	Hickey *et al.* (Ref. 14)	Schulte and Fritsch (Ref. 15)
$Cu_{42}Ti_{58}$		7	2.5	
$Cu_{44}Ti_{56}$				11
$Cu_{45}Ti_{55}$	14.5			
$Cu_{50}Ti_{50}$		4.4	1.0	6.6
$Cu_{60}Ti_{40}$	11			1.6
$Cu_{63}Ti_{37}$				1.4
$Cu_{65}Ti_{35}$	9	2.2	0.2	

applied only consider certain aspects of the problem. There is no calculation taking into account all effects, i.e., disorder, quantum corrections, nonfree electron behavior, consistently. Therefore, perfect agreement should not be expected. However, it is remarkable that the overall behavior of many amorphous alloys can be described by using these ideas.

We may now compare our $\tau_{s.o.}$'s with results of other workers. The values in Table II are in some cases adjusted for different definitions of the phase-breaking time where $\tau_{s.o.}$ is included. We have

$$\frac{1}{\tau_\phi^*}=\frac{1}{\tau_{ie}}+\frac{X}{\tau_{s.o.}}\ , \tag{2}$$

where $X=\frac{4}{3}$, 2, or 4 according to different authors. The different magnitudes of $\tau_{s.o.}$ between the reports considered are obvious. The methods and expressions in the evaluation affect severely the results. The numbers in Table II come from the magnetoresistance with the $\Delta\rho^a_{WL}$ expression[16] as well as the temperature dependence of ρ.[14,15] The tendency of an increasing $\tau_{s.o.}$ with decreasing Cu content is common for all the investigations. The strength of the composition dependence differs appreciably, however.

SUMMARY

The magnetoresistance of amorphous nonsuperconducting Cu-Ti alloys has been measured and found to be almost identical in the studied temperature and magnetic field ranges. The small and systematic differences in the experimental $\Delta\rho$ become clear in the analysis. The weak-localization theory including spin splitting was used to obtain values for $\tau_{s.o.}$. The absolute values are higher and the concentration dependence is weaker than corresponding values found by other workers using other methods or theoretical expressions. A linear concentration dependence of $\tau_{s.o.}$ is suggested by our data.

ACKNOWLEDGMENTS

We wish to thank Dr. Ö. Rapp for valuable comments on this manuscript. Part of this work has been financed by the Swedish Board for Technical Development.

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