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SUPERCONDUCTING PENETRATION DEPTH IN AMORPHOUS METALS

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We show that temperature dependent penetration depth measurements can be used to characterize the superconductive behaviour of amorphous metals.

THE MAGNETIC FIELD distribution in a superconductor in the Meissner state is characterized by the weak field penetration depth, $\lambda(T)$. The value of λ at $T = 0$ is related to properties of the normal state. Superconductivity affects only the temperature dependence of λ. It is clear that measurements of the penetration depth and its temperature dependence can provide useful information about the normal and superconducting properties of the material.

In amorphous metals the long range crystalline order is destroyed and, as a consequence, the electron mean free path (EMFP) is of the order of few interatomic distances. The zero temperature penetration depth is given by $\lambda(0) = \lambda_L(0)\sqrt{\xi_0/l}$ where $\lambda_L(0)$ and ξ_0 are respectively, the London penetration depth and the BCS coherence length of a hypothetical pure material and l is the EMFP. The EMFP correction factor, $\sqrt{\xi_0/l}$, makes $\lambda(0)$ a function of the superconducting parameter ξ_0. Although ξ_0 is not known in an amorphous material we will make the reasonable assumption that $l \ll \xi_0$. The electrodynamic response is, therefore, of local character [1]. Since the BCS theory shows that the temperature dependence of λ is determined by the superconducting energy gap $\Delta(T)$, the measurement of $\lambda(T)$ can be used [2] to determine the gap. Finally the knowledge of λ together with the determination of the Ginsburg–Landau, GL, coherence length $\xi(T)$, from measurements of the upper critical field, H_{c_2}, defines the GL parameter $\kappa = (\lambda/\xi)_{T_c}$.

We have measured the penetration depth and critical field of the amorphous $La_{0.70}Cu_{0.30}$ system which provides us with a quantitative characterization of the material and, the temperature dependence of $\lambda(T)$, reveals to what extent the BCS theory may require modification to deal with the disordered state.

The samples were ribbons 0.1 cm wide and 10^{-3} cm thick, obtained by ultrarapid quench of the molten alloy on a rotating cylinder [3]. The phase diagram of the $La_{1-x}Cu_x$ system has been studied [4] showing that the amorphous state is confined to the eutectic concentration $La_{0.70}Cu_{0.30}$. The critical temperature is found [4] to be $T_c \simeq 3.8$.

To measure the penetration depth a sample is placed in the primary of a superconducting transformer coupled to an r.f. SQUID. Sweeping temperature, at constant magnetic field, the flux variation produced by the change in $\lambda(t)$ can be measured with high accuracy.

The experimental penetration depth is defined by

$$\delta = \frac{1}{H_0}\int_0^d B(x)\,dx \qquad (1)$$

where d is the thickness of the sample, B is the local magnetic field and H_0 the applied field. In this expression, δ coincides with λ in the range of temperature in which $\lambda \ll d$. The samples investigated did not show size effects for reduced temperatures $t < 0.95$.

In our measurements H_0 was at least one order of magnitude smaller than the field at which the sample enters the mixed state. The change in flux with temperature was found to be reversible from the lowest accessible temperature, 1.4 K up to T_c. Since measurements with larger H_0 showed that the mixed state is characterized by irreversibility in the flux motion we conclude that the reversible flux variation was due to the change of $\lambda(T)$ with temperature.

One advantage, almost unique for this type of material, is that the penetration depth at $T = 0$, $\lambda(0)$, is so large that the measurement of the Meissner flux expulsion, together with the knowledge of the sample geometrical factor allows us to measure $\lambda(0)$. Thus, $\lambda(0) = (H_0Dd - \phi_M)/2H_0D$, where D is the sample width and ϕ_M is the flux expulsion in the Meissner state. In this way the value obtained for $\lambda(0) = 9.000$ Å.

The experimental $\delta(T)$ is plotted as usual as a function of $y = 1/\sqrt{1-t^4}$ as shown in Fig. 1 for two different H_0. The insert shows the low temperature data

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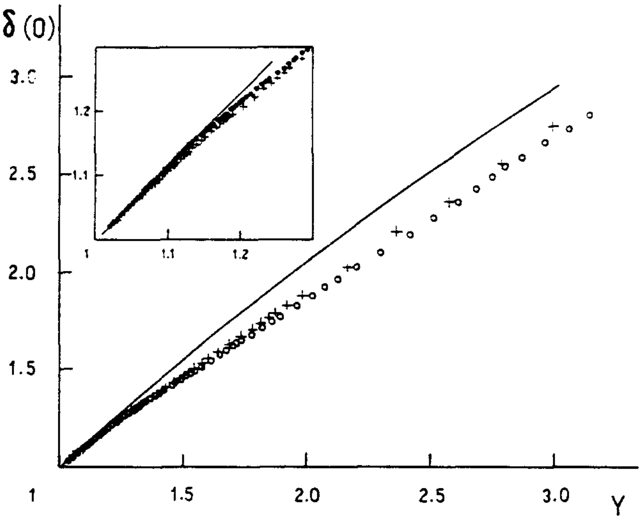

Fig. 1. $\delta(T)/\delta(0)$ vs $y = 1/\sqrt{1-(T/T_c)^4}$ for two different magnetic fields: +, 2 Oe; o 4 Oe; the continuous curve is from BCS theory with $2\Delta/kT_c = 4.5$ as explained in the text. The insert shows the same plot in the low temperature range.

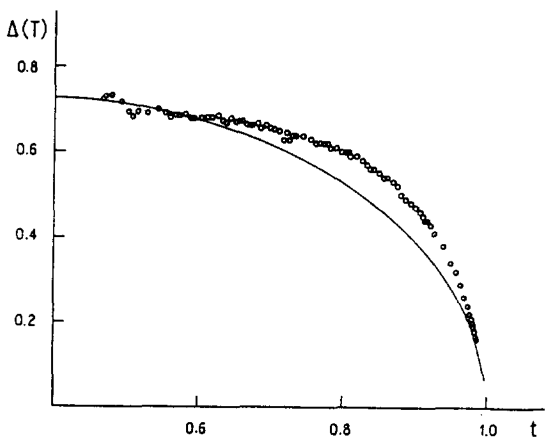

Fig. 2. "Phenomenological" or "experimental" superconducting energy gap as a function of temperature obtained by assuming the BCS relationship between $\lambda(T)$ and $\Delta(T)$ from the penetration depth measurements. The solid line is the BCS theory with $2\Delta/kT_c = 4.5$.

in an expanded scale. In the BCS theory the penetration depth is related [1] to the superconducting gap, $\Delta(T)$, through

$$\lambda(T) = \lambda_L(T)\left[\frac{\xi_0}{J(0,T)l}\right]^{1/2} \tag{2}$$

where

$$\frac{\lambda_L(T)}{\lambda_L(0)} = \left[1-\frac{1}{2}\int_0^\infty \operatorname{sech}^2\left\{\frac{1}{2}\left[y^2+\left(\frac{\Delta(T)}{kT}\right)^2\right]^{1/2}\right\}\mathrm{d}y\right]^{-1/2} \tag{3}$$

and J(RT) is defined by $\int_0^\infty J(R,T)\,\mathrm{d}R = \xi_0$. In this expression the local dirty limit has been assumed which is appropriate for disordered systems. These expressions were used to obtain the full curves in Fig. 1, where temperature dependence of the BCS gap has been assumed and $\Delta(0)/kT_c$ was left as a free parameter, so as to fit the experimental data. The full line is the BCS temperature dependence where $2\Delta(0)/kT_c = 4.5$ has been used to fit the data at low temperatures. On the other hand, if the measured $\lambda(T)/\lambda(0)$ is introduced in expressions (2) and (3) a "phenomenological" $\Delta(T)$ can be obtained. The results are shown in Fig. 2. The full line corresponds to that of Fig. 1. This result suggest that superconductivity would be of strong coupling character, in agreement with recent specific heat measurements in similar alloys [5].

From the measured $\mathrm{d}Hc_2/\mathrm{d}T$ we have obtained the GL coherence length at T_c, $\xi(0) = 64$ Å. Using the experimental $\lambda(T)$ and $\xi(T)$ the GL parameter is found to be $\kappa = 70$.

The results presented here show strong deviation from a BCS temperature dependence. The temperature dependent "gap" (see Fig. 2), is similar to that found [6] for amorphous Ga and Bi where it has been shown that the experimental data can be fitted by strong coupling theory. A similar calculation for the penetration depth in our material will require a determination of the phonon spectrum, not available at present.

In this paper we have discussed superconducting behaviour as revealed by penetration depth measurements. This work is being continued to apply these techniques to a study of the evolution of the disorder in

LaCu with annealing. Preliminary results [7] show that the change in normal properties due to the sample heat treatment below the crystallization temperature can also be easily detected by means of the change in $\lambda(0)$.

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