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SUPERCONDUCTING BEHAVIOR OF AMORPHOUS $Zr_{70}Cu_{30}$

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Measurement of the Meissner penetration depth, $\lambda(T)$ were made in amorphous $Zr_{70}Cu_{30}$ samples. The results indicate that this amorphous alloy behaves as a BCS superconductor with $2\Delta(0)/kT_c = 3.8$, where $\Delta(0)$ is the superconducting energy gap at $T = 0$ and T_c the critical temperature. It is also concluded that the low energy excitation, TLS, characteristics of amorphous material does not contribute to T_c.

THE MEISSNER PENETRATION DEPTH, $\lambda(T)$, determines the electrodynamic response of the superconducting pairs to weak magnetic fields. The absolute value of the penetration depth as well as its temperature dependence are related to the superconducting and normal properties of the electronic system. Although extensive work on the subject [1, 2] has been done in the past, the agreement between theory and experiment can be considered to be only fair. Anisotropic effects, due to real Fermi surfaces of crystalline materials, and experimental difficulties in surface preparation are usually mentioned [2, 3] as responsible for the lack of agreement either in the absolute value of $\lambda(T)$ or in its temperature dependence.

Amorphous superconductors are in principle ideal materials to avoid the two mentioned causes for experimental discrepancy. Due to the lack of long range crystalline order the electronic system of amorphous superconductors is isotropic. The high and almost temperature independent electrical resistivity indicates that the electron mean free path is of the order of interatomic distances, making the amorphous metals the best examples of dirty superconductors. The Ginzsburg–Landau parameter of these materials is large ($\kappa \simeq 100$) due to the very large penetration depth ($\lambda(0) \simeq 10{,}000$ Å) and very short coherence length ($\xi(0) \simeq 100$ Å). Under this condition, surface preparation problems are not expected to be important in the determination of the penetration depth that, by all means, should represent a bulk property of the investigated material.

There are other intrinsic properties of amorphous metals that make interesting the study of its electrodynamic superconducting response. Let us first analyze the Gorkov expression for the penetration depth in the dirty limit near T_c, given by [3]

$$\lambda_d = 0.615(\xi_0/l)^{1/2}\lambda_L(0)(1-t)^{-1/2}, \quad (1)$$

where $\lambda_L(0) = [3c^2/(8\pi e^2 v_F^2 N(0))]^{1/2}$ and $\xi_0 = 0.18hv_F/k_BT_c$. Using the simplest solution of the Boltzmann transport equation for the electrical resistivity $\rho = [\frac{2}{3}e^2 l v_F^2 N(0)]^{-1}$ the coefficient of λ_d in equation (1) can be related to accessible experimental quantities

$$\lambda_d = 0.644 \times 10^{-2}(\rho/T_c)^{1/2}(1-t)^{-1/2}, \quad (2)$$

where ρ is expressed in Ω-cm and T_c in degrees Kelvin. The electrical resistivity of amorphous $Zr_{70}Cu_{30}$ has a weak negative temperature dependence as is typically found [4] in high resistivity materials. At the present time two different theoretical approaches are commonly used in the literature to explain the electrical conduction in disordered materials. One of them [5] is based in a modification of Ziman theory for liquid metals, where the electrons are treated as plane waves interacting with atomic disorder. The other [6] considers the negative temperature coefficient of the resistivity as a manifestation of electron localization. In the absence of an accepted theory that explains the transport properties of amorphous metals and its relation to superconductivity, the experimental study of the relation given by equation (2) is important.

Another aspect to be considered in relation to expression (2) is that, although the density of states of transition metals at the Fermi surface is determined by the d character of the electronic band, it is not known which is the relative s and d contribution to the electrical conduction properties. Following the arguments given by Koepke and Bergmann [7] to discuss the upper critical field H_{c2}, it is not clear if expression (2) should apply to these d band superconductors.

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Table 1. Measured electrical resistivity, ρ, superconducting critical temperature, T_c, and transition width, ΔT_c, for the amorphous $Zr_{70}Cu_{30}$ sample. Also shown are the measured $\lambda(0)$, B and the result from Gorkov's formula [equation (2)] as explained in text

ρ ($\mu\Omega$cm)	T_c (K)	ΔT_c (K)	$\lambda(0)$ (μm)	B (μm)	$\lambda(0)$ from Eq. 2 (μm)
186	2.533	0.090	0.85	1.00	1.11

Since experimental results [8] have shown that the density of states of amorphous alloys based on transition metals, obtained from H_{c2} and specific heat, are coincident we believe that the study of the relation among T_c, ρ and λ should contribute to a better understanding of superconductivity in d-band metals.

The temperature dependence of $\lambda(T)$ provides information on the superconducting character of the material. The two-fluid model together with the London theory gives a temperature dependence of the form $\lambda(T) = \lambda_L(0)y$, where $y = (1 - t^4)^{-1/2}$. As a consequence of the energy gap in the dispersion relation of the superconducting excitations, the BCS expression [3] for $\lambda(T)$ predicts deviations from London's formula. At high temperatures, $y > 1.5$, the BCS temperature dependence is well approximated by $\lambda(t) = A + By$. Since B is a quantity easily measured it is useful [3] to characterize the material by this value that should correspond to the experimental $\lambda(0)$ for a London superconductor. On the other hand numerical calculations using the BCS theory in the local approximation show that $B = 1.23\lambda(0)$, where $\lambda(0)$ should be the measured penetration depth at $T = 0$, if the superconductor follows the BCS temperature dependence. It is important to remark that to obtain the numerical factor relating B and $\lambda(0)$ it has been assumed the weak coupling limit $2\Delta(0)/kT_c = 3.5$, where $\Delta(0)$ is the superconducting energy gap at $T = 0$.

The relation [3] between $\lambda(T)$ and $\Delta(T)$ has been used by Waldram [1] to obtain $\Delta(T)$ from penetration depth measurements of crystalline materials and recently [9] to obtain the energy gap of superconducting amorphous alloys. In the absence of tunneling data and considering that Zr_xCu_{1-x} can be considered to behave as an ideal amorphous system with a moderately strong coupling parameter [8], it is interesting to investigate if the energy gap as obtained from the penetration depth measurements follows the BCS temperature dependence.

The results discussed here were obtained from a ribbon 14.5 μm thick, 0.08 cm wide and 3 cm long, obtained from splat cooling [10] the molten metal. The resistivity, critical temperature, and transition width are given in Table 1.

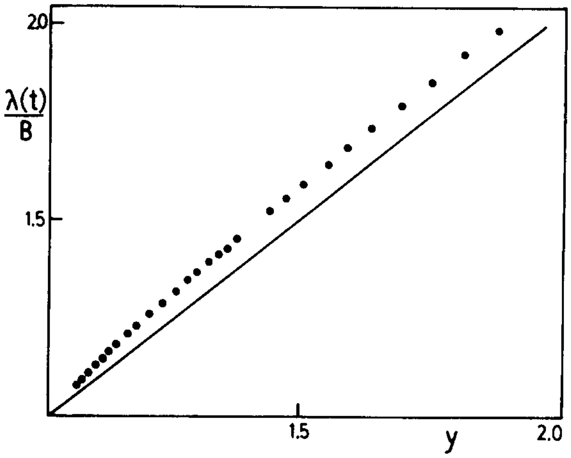

Fig. 1. Measured penetration depth $\lambda(t)$ normalized by the slope at $y > 1.5$, B, as a function of $y = (1 - t^4)^{-1/2}$. The solid line represents the London model.

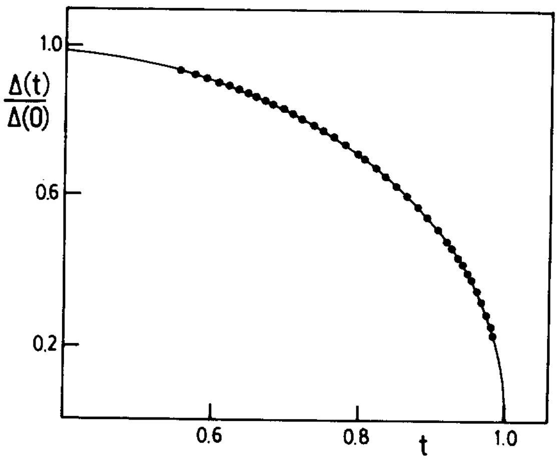

Fig. 2. Superconducting energy gap, $\Delta(t)$, as a function of $t = T/T_c$, obtained from the measured penetration depth, $\lambda(T)$, for amorphous $Zr_{70}Cu_{30}$. The solid line represents the BCS theoretical prediction for $2\Delta(0)/kT_c = 3.8$.

The flux expulsion induced by the variation of the penetration depth with temperature was measured by means of a SQUID [11]. Details on the apparatus and measuring technique can be seen in [9]. The flux expulsion and the penetration depth are related by

$$\Delta\Phi = H_0 W[\lambda(t) - \lambda(0)], \quad (3)$$

where W is the width of the sample and H_0 the applied magnetic field. At the critical temperature, expression (3) becomes

$$\Delta\Phi_M = H_0 W[d/2 - \lambda(0)], \quad (4)$$

where d is the sample thickness. This expression indicates how $\lambda(0)$ can be obtained from the total flux expulsion and geometrical factor measurements. In the high temperature region where $\lambda \sim y$ it is possible to obtain the coefficient B defined previously: from equation (3) it follows

$$B = \frac{\Delta\Phi}{\Delta y}\frac{1}{H_0 W}. \tag{5}$$

The error in the absolute value of $\lambda(0)$ is estimated in 10% due to the uncertainty in the determination of the geometrical factor. The error in B is less than 3%.

Figure 1 shows the results for $\lambda(T)$ as a function of y. The data is normalized by the slope B obtained for $y > 1.5$. The straight line represents the London temperature dependence, experimental deviations from that behavior are evident. To check if this deviation is described by the BCS theory we have evaluated the superconducting gap using Waldram's method. To obtain the gap we used $\lambda(T)/\lambda(0)$, where $\lambda(0)$ is the experimental value obtained from expression (4). Following Waldram [1] $\Delta(T)$ is obtained assuming that at a given temperature $\lambda(T)/\lambda(0)$ is related to $\Delta(T)$ by the BCS relation [3]. In our case we have used $2\Delta(0)/kT_c = 3.8$ as determined from specific heat measurements [8]. The results are shown in Fig. 2 together with the theoretical fitting. It is seen that the agreement is practically perfect. The value for $\lambda(0)$ obtained from equation (4) is given in Table 1, together with the value B obtained from equation (5). The ratio $B/\lambda(0) = 1.17$ coincides within 2% with the theoretical value obtained using $2\Delta(0)/kT_c = 3.8$. In the table we have also given the value of the penetration depth calculated from expression (2), using the experimental ρ and T_c. We see again that the agreement between Gorkov's result and the experimental B (obtained near T_c) is excellent. Measurements in other samples reproduced the results eported here within 10%.

We have shown that the electrodynamics of amorphous $Zr_{70}Cu_{30}$ is very well described by the BCS expressions in the dirty limit.

The agreement with Gorkov's relation indicates that the electrons contributing to superconductivity and electrical conductivity are the same.

Since it has been shown [4] that the low energy excitations characteristic of amorphous metals do not contribute to ρ the validity of expression (2) implies that they do not contribute to T_c either. From all this and the results for the temperature dependent gap we conclude that amorphous $Zr_{70}Cu_{30}$ is an excellent example of a BCS superconductor.

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REFERENCES

1. J.R. Waldram, *Adv. Phys.* **13**, 1 (1964).
2. W. Schwarz & J. Halbritter, *J. Appl. Phys.* **48**, 4618 (1977) (and references therein).
3. M. Tinkham, *Introduction to Superconductivity.* International Series in Pure and Applied Physics, McGraw Hill, New York (1975). A general review of the theoretical treatment and experimental results on the electrodynamic response can be found in this book.
4. J. Guimpel & F. de la Cruz, *Solid State Commun.* **44**, 1045 (1982).
5. P.J. Meisel & L.V. Cote, *Glassy Metals I.* Topics in Applied Physics, Springer Verlag, Berlin (1981).
6. Y. Imry & M. Strongin, *Phys. Rev.* **B6**, 353 (1981).
7. R. Koepke & G. Bergmann, *Solid State Commun.* **19**, 435 (1976).
8. K. Samwer & H. Lohneysen, *Phys. Rev.* **B26**, 107 (1982).
9. R. Arce, F. de la Cruz & P. Esquinazi, *Solid State Commun.* **38**, 1253 (1981).
10. H. Tutzauer, P. Esquinazi, M.E. de la Cruz & F. de la Cruz, *Rev. Sci. Instrum.* **51**, 546 (1980).
11. S.H.E. Corporation, San Diego, California, U.S.A.