Coherence and Fluctuation in 3D Networks: The Superconducting Behavior of Nb Particles Embedded in a Cu Matrix

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Abstract

We show the preparation and properties of granular samples formed by a regular distribution of spherical Nb particles, about 2 µm in diameter, embedded in a Cu matrix. Measurements of magnetization, resistance and V×I curves show clearly the combined superconducting behavior of the weak coupling and bulk regimes. Our results are interpreted using an effective medium model for the Josephson coupling in a 3D-array of grains. In special we have observed the predicted small oscillations in the critical current, measured as a function of the applied magnetic field.

Josephson Effect, Granular Superconductivity, Proximity Effect

2. Introduction

In this work, we describe a novel and efficient method aimed at preparing granular superconducting samples. A mixture of Cu-Xwt%Nb (X=3, 5, 10) was initially arc melted, followed by RF heating up to around 1950 °C. By dropping the liquid mixture inside a cold Cu container, very fast cooling rates ($\Delta T / \Delta t \approx 2800$ °C/s) were obtained, producing solid samples with Nb particles dispersed in Cu matrix. The shape and uniformity of the particles are strongly dependend on cooling rate [1]. Although several samples of Cu-Xwt%Nb have been prepared and studied, here we report results only for a sample with X=5. Fig. 1 shows a typical distribution of Nb particles, with diameters around 2 µm. This was found in some regions of the sample after applying a *rearrangement* annealing at 1100 °C, for 30 min. Because the Nb particles redistribute in similar way when immersed in liquid Cu, its final volume concentration looks almost independent on the initial Nb content.

Measurements of resistance, V×I curves and magnetization, taken with a SQUID and PPMS machines, show clearly a response of an almost bulk Nb sample, superimposed to signatures of a weak coupled system. We explain some of the results through Josephson coupling between the 3D-array of Nb particles or grains. In this model the supercurrent that flows from grain *i* to *j* is given by [2],

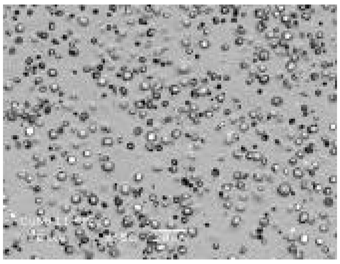

Fig. 1. SEM picture displaying spherical Nb particles dispersed in a Cu matrix.

$I = I_c(T)\sin(\text{ö}_i - \text{ö}_j - \text{ø}_{ij})$, where $I_c(T)$ is the critical current of the junction, Φ_0 is the flux quantum and the argument of sin is the gauge-invariant phase difference between the grains, with $\text{ø}_{ij} = \frac{2\text{ð}}{\Phi_0}\int_i^j \mathbf{A.dl}$.

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The Josephson coupling between randomly dispersed grains, in the presence of fields and currents, can be modeled by an effective medium theory that gives [3] :

$$I_c(H)/I_{c0} = 0.82\,[1-(KH)^{-1}\sin(KH)]^{1/2}\,H^*/H \qquad (1)$$

where H^* is the maximum field that allows perfect shielding of the sample and $K \approx 2.7(L/\lambda_J)/H^*$; L being a characteristic dimension of the sample and λ_J the coherent penetration depth.

2. Results and Discussion

Fig. 2 shows the H×T diagram, with the H_{c2} line defined at the onset of transition, associated with the bulk behavior of the Nb grains. Due to a solid solution of Cu in Nb the critical temperature of 8.3 K is about 1 K below the value expected for pure Nb. The M×T curves, for magnetic fields below 200 Oe, display a clear knee in its ZFC part. This is associated to an abrupt loss of phase coherence between grains, that allows an abrupt penetration of magnetic flux close to T_c. The H_J line was then evaluated by taking this crossover point for several M×T curves, following the criterion shown in the upper inset of Fig.2. The M×H curves show also a clear signature of the weak coupled regime, with its lower critical field $H_{c1J} = H^*$ followed by an upper critical field H_{c2J} [2]. This latter is equivalent to H_J, being located below and close to the bulk H_{c1} field (see inset of Fig. 3). Magnetic flux penetrates gradually between the Nb grains when $H_{c1J} \le H \le H_{c2J}$ as a consequence of the gradual frustration of Josephson coupling, which reduces the overall current throughout the sample. This current drops quickly for increasing H, as shown by the experimental points in Fig.3. A criterion of 10^{-7} V was employed to extract the $I_c(H)$ values from V×I curves, measured in a Cu-Nb strip of cross-section 0.01×0.2 cm^2 and 0.4 cm in length, with H perpendicular to the current. A weak oscillating behavior can be observed in the $I_c(H)$ curves, following fairly well the prediction of Eq. (1), represented by the solid line plot in Fig. 3. This plot uses $H^* = H_{c1J} = 15$ Oe, taken from the M×H curve for T = 4 K, and K = 0.265 that implies $L/\lambda_J \approx 1.5$. This latter ratio seems to be typical for granular Nb systems [3]. In our case L ≈ 0.1 cm and $\lambda_J \approx 0.06$ cm. The dashed oscilating line in Fig. 3 was obtained using the same fitted Eq. (1), but using exponent 2 instead of 1/2 in the bracket term. This is just an aid to visualize the good agreement between the observed and predicted oscillations period of H ≈ 24 Oe. If we assume a perfect planar array of identical grains, regularly spaced, then $\Phi_0 \approx 2\times10^{-7}$ $Gcm^2 \approx 24a$, where *a* would be the junction area between the grains. We find $a \approx 10^{-8}$ cm^2, meaning that the spacing between grains should be around 1 µm, which is quite compatible with our more complex 3D system. New measurements are still under way, especially aimed at improving the V×I curves. A more complete version of this work will be published elsewhere.

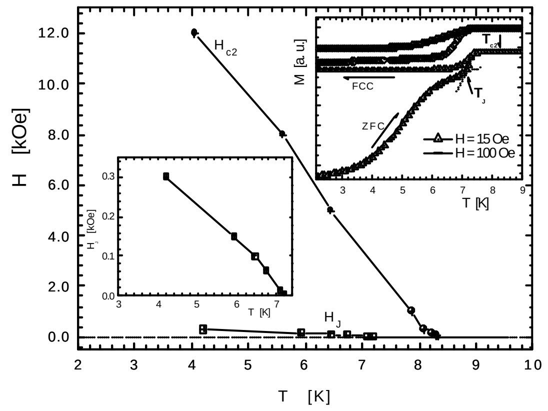

Fig. 2. H_{c2} and H_J lines defined at the onset of transition and at the weak coupling knee (see upper inset). The lower inset is an enlarged view of the H_J×T line.

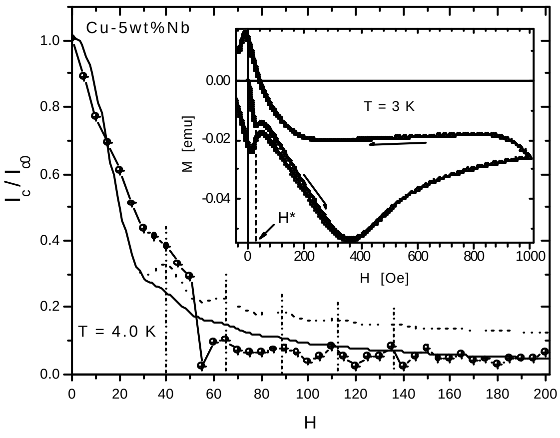

Fig. 3: The critical current (normalized to I_{c0} = 156 mA), displays an oscillating behavior as a function of H. The solid line is a fit to Eq. (1). Inset: typical M×H curve showing the combined signals from the weak coupling and bulk behavior.

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