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The resistive anomaly and upward curvature of the perpendicular upper critical field in non-homogeneous superconductors

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Abstract

A peak in the resistance versus temperature measurements, just above T_c, has been observed for perforated superconducting Nb/CuMn multilayers. The peak is present in zero magnetic field and its height becomes smaller as the perpendicular field is increased. In addition, the perpendicular critical magnetic field versus temperature curve shows an upward positive curvature. By considering a simple concentrated constant-equivalent circuit we have reproduced the observed resistive transitions and the upper perpendicular critical magnetic field behaviour.

A resistance anomaly consisting in a large enhancement of the resistance R above its normal-state value R_N, close to the superconducting critical temperature T_c, has been observed for different non-homogeneous thin films [1–3]. Similar effects, observed for narrow Al mesoscopic structures, are also reported in the literature and have been related to the quasi-one-dimensional nature of the system and to the presence of phase slip centres or to intrinsic normal/superconducting interfaces [4, 5]. However, it has been shown that the presence of rf noise could also provide an extrinsic origin of the enhancement of the resistance [6]. For bidimensional granular samples, a simple explanation, based on a current redistribution due to the sample inhomogeneities when measuring in an out-of-line contact arrangement, has been recently proposed [3]. The appearance of this anomalous superconducting transition in granular superconductors has also been related to the occurrence of superconductor–insulator–superconductor (SIS) tunnelling at the grain boundaries across the film width [7].

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Furthermore, a concave-upward curvature in the perpendicular critical magnetic field $H_{c2\perp}$ versus the temperature curve has been observed for a great number of different superconducting systems [8–14] and several interpretations have been given to explain this effect. They include scattering by magnetic impurities [15], reduced dimensionality and disorder non-homogeneity effects [16], strong electron–phonon coupling [17], and bipolaron effects [18].

We have measured a peak in the resistance versus temperature curves for Nb/CuMn multilayers, just above T_c. The peak is present in zero magnetic field and its height becomes smaller as the perpendicular field is increased up to values of the order of tenths of a tesla. Moreover, the $H_{c2\perp}(T)$ curve, for these multilayers, presents an upward-concave curvature. By using a simple model, we show that both the presence of the peak and the upward curvature observed in the $H_{c2\perp}(T)$ curve can be related to the non-homogeneity in the superconducting properties of the sample.

The samples for which we have observed the presence of the peak in the $R(T)$ curves had regular arrays of holes fabricated using electron-beam lithography. The Nb and CuMn layers were deposited by a dual-source magnetically enhanced dc triode sputtering system with a movable substrate holder onto the electron-beam-patterned resist present on the Si(100) wafer used as the substrate. The resulting structures were obtained by the lift-off technique. Each hole has a circular geometry and the holes are arranged in a square-lattice configuration, with total dimensions of $200 \times 200\ \mu\mathrm{m}^2$ and four separate contact pads connected to the four vertices of the array in a van der Pauw configuration (figure 1, inset). The hole diameter was

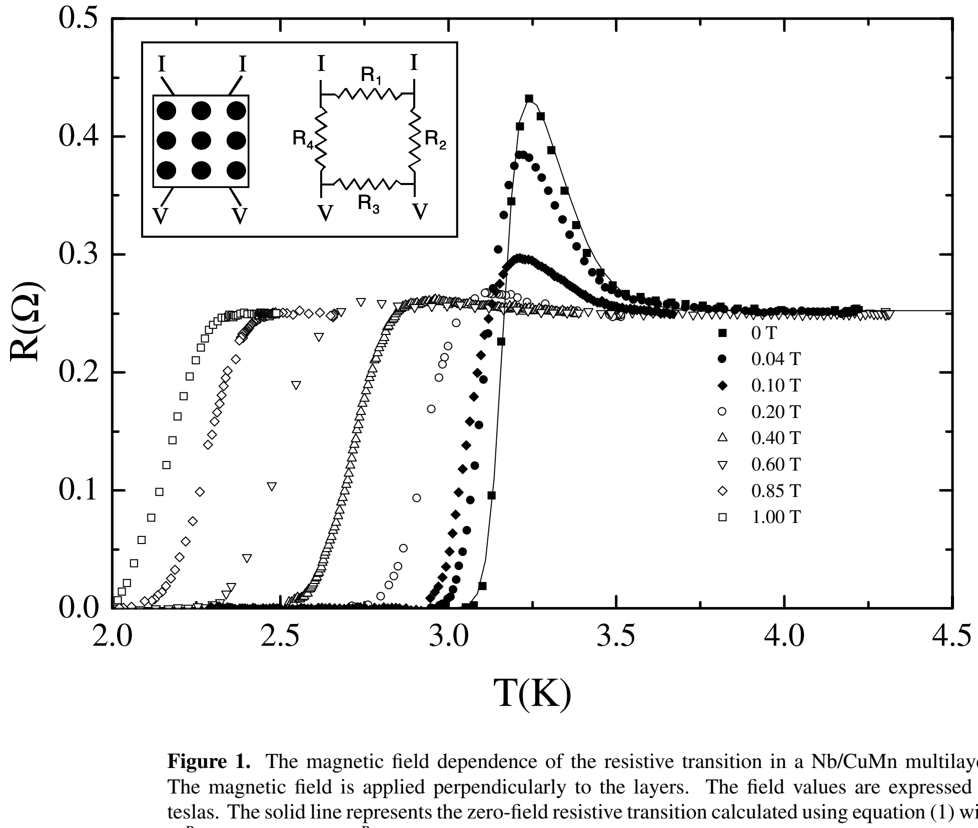


Figure 1. The magnetic field dependence of the resistive transition in a Nb/CuMn multilayer. The magnetic field is applied perpendicularly to the layers. The field values are expressed in teslas. The solid line represents the zero-field resistive transition calculated using equation (1) with $T_c^{R_2} = 3.33$ K and $T_c^{R_1} = 3.1$ K. Inset: the four-contact configuration for our sample and the CCEC model.

$D \approx 1\ \mu$m and the period of the structure was $d \approx 2\ \mu$m. The number of bilayers is equal to six. The first layer is CuMn; the last one is Nb [19]. The role played by the presence of the holes in our samples is related to the enhancement of the non-homogeneity. There are various possible causes of this enhancement, such as zones with different superconducting properties (for example, close to the holes and far from them) and current-density redistribution induced by the bottleneck between the holes.

In figure 1 the resistive transitions of a perforated multilayer measured for different values of the perpendicular magnetic field are reported. The measurements were performed using a standard four-terminal dc technique with a bias current of 100 μA. The final accuracy in the resistance measurements was $\sim 10^{-4}\ \Omega$. The sample shown in figure 1 has a Nb thickness, d_{Nb}, equal to 250 Å, while the CuMn thickness, d_{CuMn}, is 13 Å. The Mn percentage is equal to 2.7. A peak in the resistive curve in zero field, with an amplitude that is nearly 100% of the R_N-value, is clearly present.

The amplitude of the peak in figure 1 decreases as the field is increased and it disappears completely for $\mu_0 H = 0.6$ T. Another effect of the magnetic field is a shift of the resistive transition curves towards lower temperatures that does not cause any appreciable broadening of the curves themselves. This makes it very simple to define $H_{c2\perp}(T)$, which can be determined unambiguously. We have observed similar peaks for different superconducting thin films of NbN, VN, NbTiN, and Nb/Cu and Nb/Pd multilayers. Whenever the peak was detected, the four-contact arrangement, sketched in the inset of figure 1, had been used. On the other hand, the peak was never observed when an in-line contact arrangement was used. In figure 2 the temperature dependence of the upper perpendicular critical field is reported for the same sample, showing an upward positive curvature with a value of $\mathrm{d}^2 H/\mathrm{d}T^2 = 0.28$ T K^{-2}. The critical field has been taken at the point where $R(T, H) = R_N/2$.

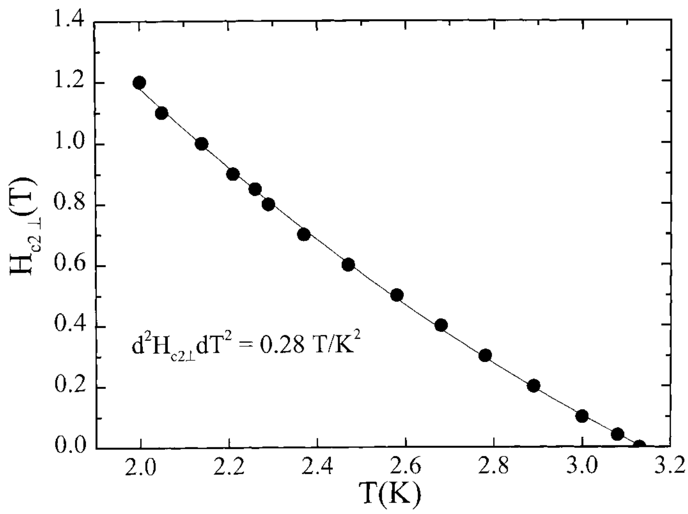


Figure 2. The temperature dependence of the upper perpendicular critical magnetic field for the Nb/CuMn multilayer of figure 1. The solid line is the best-fit curve for the experimental data, having $\mathrm{d}^2 H_{c2}/\mathrm{d}T^2 = 0.28$ T K^{-2}.

The peak at zero magnetic field in the resistive transition is easily reproduced by considering simultaneously the non-homogeneity of the samples and the geometry of the electrical probes. In fact, the measured resistance $R_m = V/I$ for our samples, in the configuration of the inset in figure 1, is given by [3]

$$R_m = R_1 R_3 \Big/ \sum_{i=1}^{4} R_i \tag{1}$$

where we are assuming a simple concentrated constant-equivalent circuit (CCEC) with resistances R_1, R_2, R_3, and R_4 between each couple of probes [3]. Because of the non-homogeneity of our samples, the four resistors can have different transition temperatures. For further simplicity, we have also assumed $R_1 = R_3$ and $R_2 = R_4$ at all of the temperatures. From equation (1) it is clear that a resistance drop of R_2 or R_4 produces a sharp increase in R_m. Using equation (1) we can fit the zero-magnetic-field $R(T)$ curve (the solid line in figure 1) by taking $T_c^{R_2} = 3.33$ K $> T_c^{R_1} = 3.1$ K [3]. We point out that in the case of an in-line contact arrangement, in the same CCEC approximation, the measured resistance R'_m is given by

$$R'_m = R_1(R_1 + R_2 + R_3) \Big/ \sum_{i=1}^{4} R_i \tag{2}$$

and the peak is not present when R_2 and R_4 go to zero.

Furthermore, it is reasonable to assume that two zones having different transition temperatures are also characterized by different critical magnetic fields. In particular, if we relate the slight T_c-depression to the presence of disorder [20], then we must have $H_{c2}^{(R_1)}(0) > H_{c2}^{(R_2)}(0)$, where $H_{c2}^{(R_1)}(0)$ and $H_{c2}^{(R_2)}(0)$ are, respectively, the zero-temperature critical magnetic fields of the zones described by the resistors R_1 and R_2. In fact, in the particular case of the dirty limit [21], $H_{c2}(0) \sim 1/\xi^2(0) \sim 1/(\xi_0 \ell)$, where ξ is the superconducting coherence length in the dirty superconductor, ξ_0 is the corresponding BCS quantity in the clean limit, and ℓ is the electronic mean free path. It is then clear that, if ℓ decreases (i.e. the disorder increases), then $H_{c2}(0)$ increases while T_c goes down.

Assuming a linear temperature dependence for the critical magnetic field:

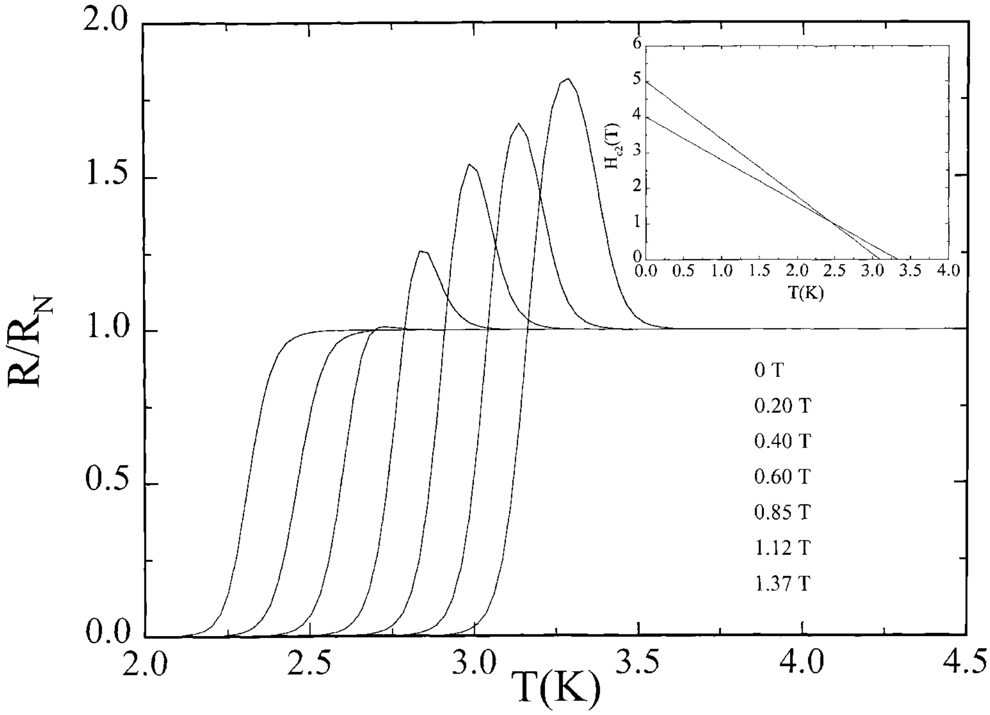
$$H_{c2}^{(R_i)}(T) = H_{c2}^{(R_i)}(0)\left(1 - \frac{T}{T_c^{R_i}}\right) \qquad \text{for } i = 1, 2 \tag{3}$$

the two curves will clearly cross in the H–T plane (see the inset in figure 3(a)). Here $T_c^{R_i}$ represents the zero-magnetic-field critical temperature of the resistance R_i, or, alternatively, the critical temperature of one of the two zones into which we have separated our superconducting system. With these expressions for $H_{c2}^{(R_i)}(T)$, the peak in the resistive transitions, calculated using equation (1), is present only for magnetic field values less than the crossing value, in the temperature range where $T_c^{R_2} > T_c^{R_1}$. In fact, at temperatures below the crossing point, $R_1(T, H)$ will go to zero before $R_2(T, H)$, and from equation (1) it is clear that $R_m(T, H)$ will also go to zero along with $R_1(T, H)$ without any peak.

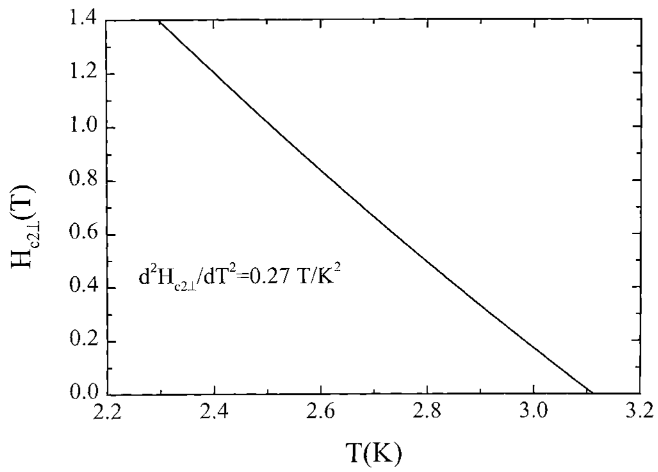
Taking the values for the critical temperatures used in the case of the best fit in figure 1, and assuming $H_{c2}^{(R_1)}(0) = 5$ T and $H_{c2}^{(R_2)}(0) = 4$ T, through the use of equations (1) and (3) we have obtained the family of $R(T, H)$ curves shown in figure 3(a). They qualitatively describe well the experimental behaviour observed for our samples and shown in figure 1. The peak disappears at magnetic fields of the order of a tesla, close to the experimentally measured value.

Moreover, from the curves in figure 3(a), we have extracted the critical magnetic field values (defined as the points where $R(T, H) = R_N/2$) at different temperatures; the results are reported in figure 3(b). The $H_{c2\perp}(T)$ theoretical curve shows an upward curvature with a value of $\mathrm{d}^2H/\mathrm{d}T^2 = 0.27$ T K^{-2}, again very close to that of the experimental $H_{c2\perp}(T)$ curve of figure 2.

In spite of the crudeness of the proposed model, figures 3(a) and 3(b) contain the essential features of the experimental results: the presence of the peak in the resistive transitions



(a)



(b)

Figure 3. The magnetic field dependence of the resistive transition (a) and the temperature dependence of the upper perpendicular critical magnetic field (b), calculated using the simple concentrated constant-equivalent circuit described in the text. In (a) the field values are expressed in teslas. The inset in (a) shows the assumed temperature dependence of the critical magnetic field for the two different zones in the sample. The curve in (b) has a positive curvature with $d^2H_{c2}/dT^2 = 0.27$ T K^{-2}.

becoming smaller as the magnetic field is increased, and the upward curvature present in the $H_{c2\perp}(T)$ curve. Due to the simplicity of the model, however, quantitative reproduction of all of the resistive transitions in figure 1 is not feasible. A quantitative fit of the experimental data could be obtained, for example, by considering more than two different superconducting zones in the sample or an $H_{c2}(T)$ dependence different from the linear one predicted by equation (3). In this case, the system will be characterized by a distribution of critical temperatures and the simple equation (1) will be replaced by a more complicated relation. In fact, since in a resistanceless network the currents carried in parallel paths are inversely proportional to the self-inductances of those paths, it may be expected that some currents will flow proportionally to the self-inductances of such paths [22]. However, we want to point out that even in the very crude and simple model presented, the presence of the peak in the $R(T)$ curves and the upward-concave curvature of the $H_{c2\perp}(T)$ behaviour can be consistently related to the non-homogeneity of the samples. We also stress that we never observed a peak in the $R(T)$ curves or obtained an upward curvature in the $H_{c2\perp}(T)$ curves when an in-line contact arrangement was used. This rules out the possibility that the above-observed effects are related to the presence of magnetic impurities in the superconductor due to the interdiffusion at the interfaces or to effects of reduced dimensionality in our experimental system.

Finally, the curvature of the upper perpendicular critical field cannot be explained in the framework of the model based on the presence of Josephson junctions in non-homogeneous superconductors [7] which also cannot reproduce the presence of the peak in the resistive transitions up to magnetic fields as high as 0.5 T.

In conclusion, by considering a simple concentrated constant-equivalent circuit we have been able to reproduce the peak in the resistive transitions and the concave perpendicular critical magnetic fields observed in non-homogeneous Nb/CuMn multilayers. Even though additional mechanisms can be proposed, the main experimental observations are reproduced simply by assuming the presence of superconducting paths having different transition temperatures and upper critical fields.

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