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Anisotropic magnetotransport in high temperature superconductor multilayers

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The high temperature superconducting cuprates are layered materials in which the CuO_2 layers are found to play an important role for the superconducting properties. When produced in thin film form, these materials can be grown in a layer by layer sequence and this has allowed us to make superlattices of various combinations of these compounds. In particular, in the $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ system it is possible to produce superlattices where the individual layers are as thin as one *c*-axis unit cell. This allows us to modify the anisotropy of these materials in a controlled manner. In this contribution we present a study of the resistive transition in a magnetic field perpendicular or parallel to the layers, and how the results can be used to gain insight into the role of the anisotropy for the dissipative behaviour of these high temperature superconductors.

1. Introduction

A characteristic feature of the high temperature superconducting cuprates is their layered crystal structure [1]. The essential structural element with regard to superconductivity is generally believed to be the CuO_2 planes present in all these compounds. The structure can be thought of as a stack of various metal oxide layers containing one or several CuO_2 planes per unit cell. The superconducting properties are clearly a function of the type of metal oxygen layers present as well as their stacking sequence. This layered crystal structure gives these materials highly anisotropic properties and they behave in many ways as quasi 2-dimensional compounds. It is therefore of particular importance to understand the role that the reduced dimensionality plays, both for the occurrence of high temperature superconductivity in these compounds as well as for their superconducting properties.

Since the discovery of this class of superconductors, considerable progress has been made in the synthesis of thin films. It has in particular been found that it is possible to grow these materials in a layer by layer mode with individual layers as thin as the unit cell thickness and thus to produce artificial multilayers. The first materials to be produced this way were multilayers of the type $YBa_2Cu_3O_7$/$DyBa_2Cu_3O_7$(YBCO/DyBCO) [2] and $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ [3], where the individual layers could be as thin as one *c*-axis unit cell. Since then several groups have produced these and other types of multilayers [4–10], and it appears that such multilayer techniques will become important both to produce new materials and for the fabrication of heterostructures foı future applications. In this paper we shall discuss the properties of the YBCO/PrBCO multilayers, grown on MgO or on $SrTiO_3$ substrates and having the *c*-axis perpendicular to the film plane. For details of the fabrication we refer to the literature [11].

The reason for studying these multilayers is that PrBCO is an insulator (with a hopping like conductivity at low temperature). Thus, inserting PrBCO layers between the YBCO layers will

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have the effect of decoupling the latter and it is thus possible to modify the anisotropy of the material in a controlled manner. For large PrBCO thicknesses, one can separate the YBCO layers completely and thus allow the study of ultrathin superconducting layers even as thin as one unit cell. In the following we shall discuss the influence of the anisotropy and the quasi 2-dimensional nature of the multilayer on the resistive transition in magnetic fields either perpendicular to the layers (i.e. parallel to the c-axis) or parallel to the layers (i.e. perpendicular to the c-axis) [12–15].

2. Resistive transitions in ultrathin YBCO layers

One question that has been addressed by several groups is that related to the coupling between individual CuO_2 double layers and its importance for the high critical temperature. Experiments on series of multilayers where the individual YBCO layers, one, two or several lattice parameters thick, are separated by PrBCO layers with increasing thickness, show that T_c decreases as the PrBCO thickness is increased up to thicknesses of the order of 50–60 Å [3–5]. Beyond that, one finds that T_c remains independent of the PrBCO thickness. The origin of this apparent coupling across relatively thick PrBCO layers has been the object of several theoretical studies recently [16–18]. A discussion of this question can be found in ref. [19]. In the magnetoresistive investigations to be presented below, we find evidence that the Josephson type coupling disappears when the PrBCO thickness exceeds 24 Å. In any case, when the PrBCO thickness is larger than 60 Å we may safely assume that the YBCO layers are uncoupled and behave as independent layers. In fig. 1 we show the transitions of a YBCO film, and two multilayers, 24 Å/96 Å and 96 Å/96 Å. As can be seen, when the individual YBCO layers are made thinner, the onset of the resistive transition shifts to lower temperatures and the transition gets broader. The shift of the onset may either be due to the missing interlayer BCS interaction at the interface or to a pairbreaking, or a kind of proximity effect, due to the PrBCO layer. The broadening on the other hand is expected to be related to 2D fluctuation effects [3] with the possibility of a Kosterlitz–Thouless transition where the resistivity goes to zero. This question is presently being investigated by several groups [20–22].

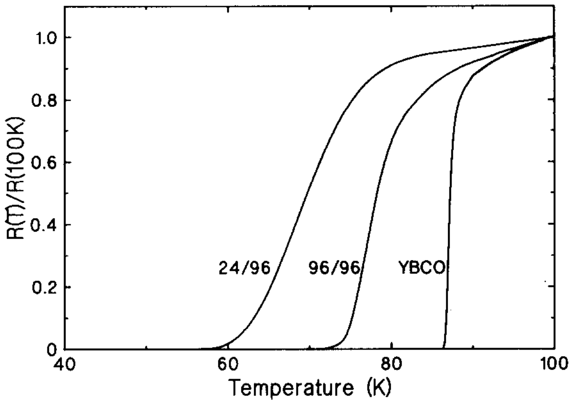

Fig. 1. Resistive transitions for a 24 Å/96 Å and a 96 Å/96 Å superlattice compared to the transition of a YBCO film.

When a magnetic field is applied perpendicular to the layers (i.e. parallel to the c-axis) one observes a marked broadening of the resistive transition. Compared to the conventional superconductors where the field usually produces a shift, this is a characteristic property of the high temperature superconductors and has triggered numerous investigations. The general understanding of this behaviour is that the shift due to a finite value of the upper critical field is very small since H_{c2} is very high in the high temperature superconductors and that the broadening results from flux motion related dissipation in the superconducting state. As an example we show in fig. 2 the resistive transitions of the 96 Å/96 Å multilayer for fields of 0, 1, 3, 6 and 9 T. It is an experimental fact that the more 2D-like the superconductor is, the more important is the broadening. In the next section we shall describe how one can use the superlattices to obtain information about the mechanisms responsible for the dissipation in the superconducting state.

When the field is applied parallel to the planes (i.e. perpendicular to the c-axis), a broadening is also observed in pure YBCO, but this one is less important than for the other field orientation.

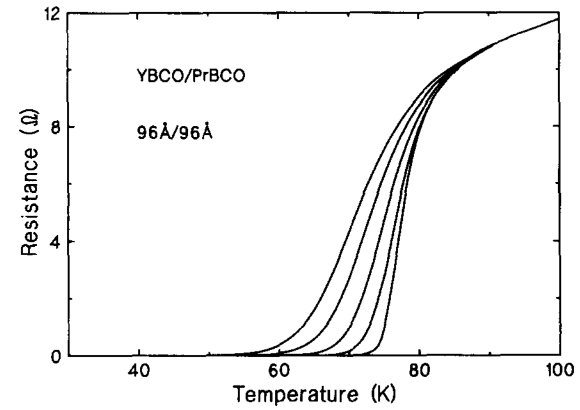

Fig. 2. Resistive transitions of a 96 Å/96 Å multilayer for five selected magnetic fields (0, 1, 3, 6 and 9 T) oriented perpendicular to the a, b plane.

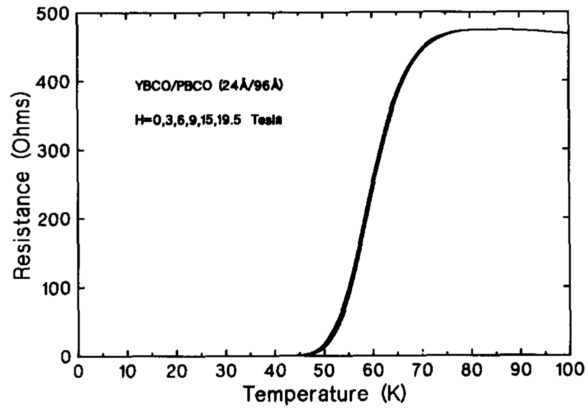

Fig. 3. Temperature dependence of the electrical resistance of a 24 Å/96 Å multilayer in magnetic fields oriented parallel to the basal plane and ranging from 0 to 19.5 T.

When the anisotropy increases, the broadening in this field orientation decreases and finally for the 2D case of the 24 Å/96 Å superlattice, the magnetic field has no significant effect on the resistive transition up to 19.5 T as illustrated in fig. 3.

3. Thermally activated flux motion in YBCO/PrBCO multilayers

3.1. *Field perpendicular to the a,b plane*

In a superconductor, placed in a magnetic field, dissipation is thought to result from the movement of individual flux lines or from the movement of flux bundles. In an ideal type II superconductor, the application of a current will produce a Lorentz force and provoke a movement of the flux lines and thus a dissipation. In a real superconductor, inhomogeneities which pin the vortices are always present, leading to a finite critical current. When the temperature is raised towards T_c, it is expected that there exists a so-called glass transition [23, 24] above which an Ohmic behaviour is found and thus no real critical current, although the dissipation might still be at a very low level. At a still higher temperature, a real melting of the flux line lattice might occur.

All these properties are closely related to the anisotropy and the quasi 2D nature of the high temperature superconductors and we describe here how we have used our superlattices to study some of these properties. For the results presented in this paper we have limited ourselves to the regime where the current voltage characteristics are linear, i.e. above the temperature where a glass transition is supposed to take place. Furthermore, referring to fig. 2 we investigate the temperature regime where $R(T)/R_n < 10^{-2}$ (R_n is the normal state resistance just above T_c). In this domain, the temperature dependence of the resistivity has been reported to be of an activated Arrhenius type [25, 26] with a dissipation corresponding to a thermally activated flux flow [27, 28]. In fig. 4 we show the Arrhenius plots for the 96 Å/96 Å sample. At low resistance ratios $R(T)/R_n$, a nearly straight line behaviour is observed corresponding to

$$\ln\left(\frac{R(T)}{R_n}\right) = \frac{-U(T,H)}{k_B T} .$$

The fact that the Arrhenius plots are very close to linear shows that the temperature dependence of the activation energy $U(T, H)$ is very close to linear, i.e. $1 - T/T_c$. To extract the activation energy at a given field, one has in principle to correct for the temperature dependence of U. It turns out that this correction is small for multilayers with thin individual YBCO layers and that a straightforward determination of the average slope in the Arrhenius plot gives values very

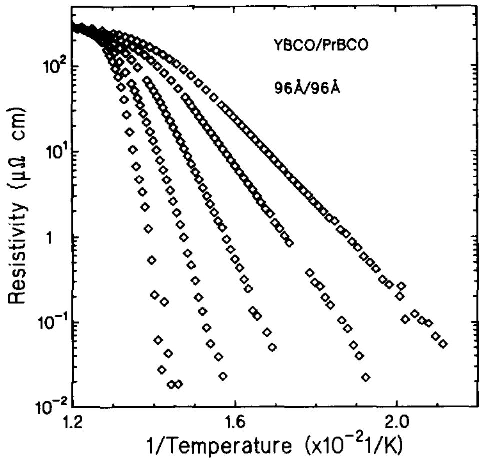

Fig. 4. Resistivity $\rho(T, H)$ versus $1/T$ for a 96 Å/96 Å superlattice and for fields of 0, 1, 3, 6, and 9 T. The magnetic field is applied parallel to the c-axis.

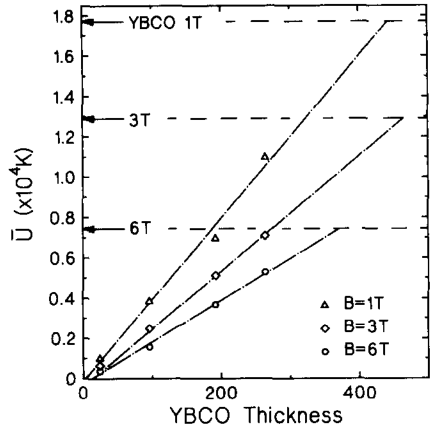

Fig. 5. Activation energy at 1, 3 and 6 T as a function of the YBCO thickness in multilayers with thick PrBCO separation thicknesses. The arrows show the values for a 1500 Å YBCO thick film. The magnetic field is applied perpendicular to the a, b plane.

close to those found in more detailed investigation. For a discussion of this point we refer to refs. [12, 28]. In this paper we shall determine U from a linear fit to the data in the interval $10^{-4} < R(T)/R_n < 10^{-2}$ and we denote the experimentally determined activation energy, $\bar{U}$. To study the influence of the quasi 2-dimensional nature on the thermally activated flux flow one can either keep the YBCO layers at a constant thickness and vary the PrBCO thickness to change the coupling between the YBCO layers, or one can make the PrBCO layers thick enough that no effective coupling is present and then vary the YBCO thickness. In the work reported here we have followed the second approach. We first verified that 48 Å of PrBCO is enough to completely uncouple the layers for the present investigations. We then studied the behaviour of the thermally activated flux flow for YBCO thicknesses of 24, 96, 192 and 264 Å. A first important result is that in these thin layers and for a given field, the activation energy increases proportional to the thickness of the individual layers. This is illustrated in fig. 5. Thus the thinner the individual layers are, the higher the dissipation at a given T and B will be. Note that this d-dependence continues up to relatively large thicknesses.

We have also studied the magnetic field dependence of the activation energy. In fig. 6 we plot $\bar{U}$ versus log B for the 24 Å/96 Å and the 96 Å/96 Å multilayers. In the investigated field interval we find that $\bar{U}$ follows very closely a logarithmic field dependence. This is also true for other multilayers investigated here and by dividing by the thickness we can reduce all data to one field dependence $\bar{U}/d = -\alpha \ln B + \beta$ with $\alpha = 13 \pm 3$ K/Å and $\beta = 45 \pm 5$ K/Å and B in tesla [12]. The errors reflect the scatter between the samples.

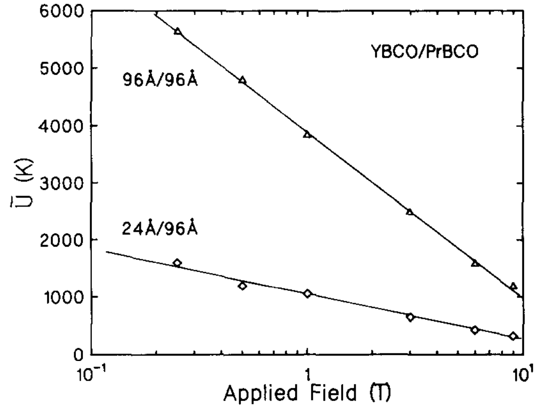

Fig. 6. Activation energy versus log B for a 24 Å/96 Å and a 96 Å/96 Å superlattice. The magnetic field is applied perpendicular to the a, b plane.

Turning now to a discussion of these results we note that a central question in the discussion of the flux flow behaviour of the high temperature superconductors, is the question to what extent the CuO_2 layers are coupled. One possible starting point would be to consider the individual CuO_2 double layers in YBCO as independent from each other (i.e. no Josephson coupling) and that the "flux line" is made up of a stack of independent point vortices or pancake vortices which are only coupled by electromagnetic interaction [30]. The latter would imply that sufficiently close to T_c the individual pancake vortices in the stack can move independently of the others. The opposite situation would be that there is a sufficiently strong interlayer coupling in YBCO that the vortices are 3D. In this case the vortices have a certain stiffness with a tilt modulus that increases with increasing interlayer coupling. To discuss our results we need to find the smallest energy that can activate flux motion. In the former hypothesis this would be a single pancake vortex or a "bundle" of such vortices in the same plane. If this is the case, then the various multilayers should all have basically the same activation energy. This is not the case since we observe that $\bar{U}$ is proportional to the thickness of the layers.

In the second hypothesis, the stiffness of the flux line resulting from the interlayer coupling means that an activated process necessarily involves a minimum length, called the correlation length L_c. If in bulk YBCO, this length is of the order of several hundred ångstroms then, with the individual YBCO layers thinner than L_c, the minimum volume of a flux bundle that can be moved is limited by the thickness of the YBCO layer. Since the activation energy must be given by an energy density times a correlation volume, we expect in this case an activation energy proportional to d, as observed. Furthermore, comparison with the activation energy of a 1500 Å YBCO film leads to the conclusion that the correlation length in the latter is of the order of 450 Å as illustrated in fig. 5. This value must be considered as a lower limit for bulk YBCO. However, it is important to notice, when comparing with other experiments, that the exact notion of a correlation length may depend on the physical property discussed and the value of L_c may furthermore depend on properties such as the critical current.

We therefore conclude that a finite coupling exists between the CuO_2 planes in YBCO and that this material is a 3D anisotropic one, with a correlation length L_c for these measurements of several hundred Ångstroms. We furthermore interpret the d-dependence of $\bar{U}$ to mean that in our very thin layers, the flux lines behave as stiff rods and that the flux line lattice is in the 2D limit in these multilayers. Feigel'man et al. [24] and Vinokur et al. [28] have considered the thermally activated flux motion in two dimensions. They conclude that the dissipation is related to the activation of dislocation pairs in the flux line lattice. When treating this in the collective pinning model Feigel'man et al. obtained an expression that can be written approximately as

$$U(T, B) = \left(\frac{\Phi_0^2 d}{16\pi^2\lambda^2(T)}\right)\log\left(\frac{a_0}{\xi_0}\right).$$

Here d is the thickness of the individual layers, Φ_0 the flux quantum, λ the penetration depth, a_0 the flux line lattice spacing and ξ_0 the coherence length. Introducing known values for λ and ξ_0 (1400 Å and 20 Å) we can write this expression as $U/d = -3.7 \ln B \pm 24$ K/Å and B in tesla. Taking into account the approximate nature of this expression, the agreement with experiment is striking. Thus without making definitive statements about the origin of the dissipation mechanism, we think that our data give quite strong support for an interpretation in terms of the thermal excitation of 2D dislocation pairs. However, we expect that as the thickness of the layers gets larger, we should gradually enter into a 3D regime where the tilt of the vortices will become important and where both the temperature and the field dependence of the activation energy will change.

3.2. Field parallel to the a, b plane

In this case we have a very different situation. The flux lines have an ellipsoidal cross-section and the coupling in the field direction is expected to be large. For the case where a Josephson coupling is present across the PrBCO, flux lines will tend to be pinned between the layers. However, for the case considered here where the PrBCO layers are thick, we expect only weak screening currents in the YBCO layers at low fields. As the field increases and reaches H_{c1} of the individual YBCO layers, the fluxlines will penetrate inside the layers. Thus if the magnetic field induced broadening is related to flux line movements it should be absent up to fields of the order of H_{c1}. Figure 7 shows the Arrhenius plots

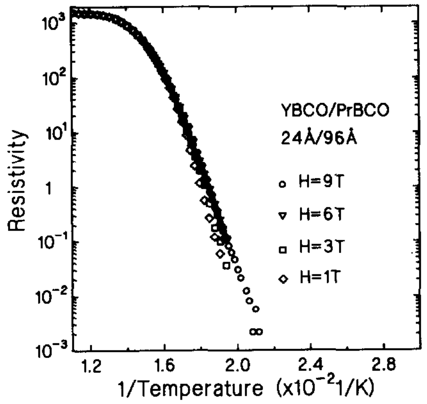

Fig. 7. Resistivity $\rho(T, H)$ versus $1/T$ for a 24 Å/96 Å superlattice for different magnetic fields applied parallel to the a, b plane (0, 1, 3, 6 and 9 T).

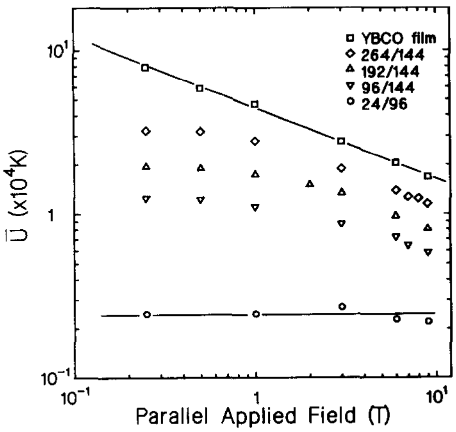

Fig. 8. Log $\bar{U}$ versus log B for a YBCO thin film and four superlattices: 24 Å/96 Å, 96 Å/96 Å, 192 Å/144 Å and 264 Å/144 Å. The magnetic field is applied parallel to the a, b plane.

for the 24 Å/96 Å multilayer. Indeed, we observe no field dependence of $\bar{U}$. In fig. 8 we show the activation energies for several multilayers as a function of field. Also for those with thicker YBCO layers we find that $\bar{U}$ is field independent at low fields. However, at higher fields we find that there is a crossover to a power law behaviour similar to that observed in a 1500 Å thick film. A preliminary analysis of these data suggests that the crossover actually occurs when the field reaches a value of the order of H_{c1} [31]. This is consistent with the observation that no broadening occurs in the 24 Å/96 Å superlattice even up to 20 T.

4. Concluding remarks

The fabrication of multilayers of high temperature superconductors has allowed investigations of the properties of ultrathin superconducting layers and of the role that the anisotropy plays in these materials. We find that the more 2D like the material, the more important the thermally activated dissipation. In the perpendicular field orientation we find evidence for dissipation related to the thermal activation of dislocation pairs in the 2D flux line lattice when the individual YBCO layers are thin enough. When the thickness of these layers gets large, typically beyond 200 Å, we expect a gradual transition to a 3D behaviour where the activation energy will also be influenced by the bending of the flux lines. When the field is parallel to the layers we observe a remarkable field independence of the resistive transition for the 24 Å/96 Å multilayer. For thicker YBCO layers we find evidence for a cross over to "bulk" behaviour at fields higher than H_{c1} of the individual YBCO layers.

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