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Field Enhanced Intrinsic Fluctuations in Highly Oriented High T_c Thin Films*

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Abstract

Experimental resistance versus temperature plots measured in various magnetic fields up to 7 T in strength are presented for highly oriented YBaCu oxide thin films deposited onto crystalline zirconia. Possible broadening mechanisms are summarised and a detailed analysis made for three models which involve processes intrinsic to the ideal superconducting material. It is shown that two distinct potentials may be needed to understand flux pinning in different temperature ranges below T_c. These two potentials have quite different temperature and field dependence.

1. Introduction

Transport properties of high T_c superconducting thin films in the presence of large magnetic fields provide insight into the potential of these materials to support very large current densities. However, conclusions as to their ultimate usefulness must take account of the large anisotropy in the critical current and how this is related to the ability to immobilise flux for various field and current directions. In the case of oriented thin films some reports have drawn pessimistic conclusions on the basis of measurements with the field normal to the film (parallel to the *c*-axis). Results are dramatically different for fields lying anywhere in the *ab* plane where the flux lattice is very stable up to quite high temperatures. We have examined resistance versus temperature in high magnetic fields for well oriented thin film samples of similar thickness but different microstructure. A striking feature of the results is that the dominant processes have a universal character described by parameters with a narrow range of values for different samples, and even between different classes of high T_c materials. This, and other features we discuss, point to dissipative mechanisms which are intrinsic to the pure material rather than associated with defects. Defect related phenomena should show much greater variability between samples and even within a single sample. All the mechanisms we analyse are intrinsic to bulk material and not due to grain boundaries or defects.

We present our own data exemplifying this for high quality oriented films of YBaCu oxide and analyse it in terms of three possible models. We also

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demonstrate that we are in a strongly pinned regime where there is no flux motion due to Lorentz forces. Therefore, any resistance appearing at temperatures below the zero field transition temperature must be due either to thermally activated flux motion or a strong depression of T_c accompanied by critical fluctuations which reduce the resistance in the normal state. It is possible that the observed broadening in the transitions for fields in the *c* direction has different origins to the much weaker broadening for fields in the *ab* plane.

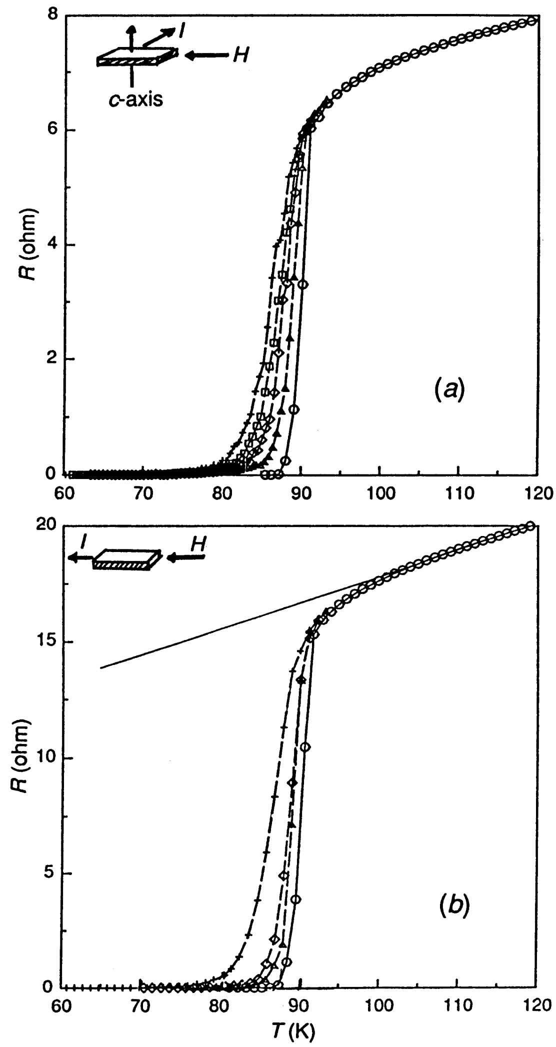

Fig. 1. Resistance versus temperature data: (*a*) The applied magnetic field is parallel to the film surface (and the *ab* plane) but normal to the current direction. Field strengths: 0 T (circles), 1 T (triangles), 3 T (diamonds), 5 T (squares) and 7 T (crosses). (*b*) The field is parallel to the current. Field strengths: 0 T (circles), 0·1 T (triangles), 1 T (diamonds) and 7 T (crosses). (*c*) The field is perpendicular to the film (and parallel to the *c*-direction). Symbols are as in part (*a*).

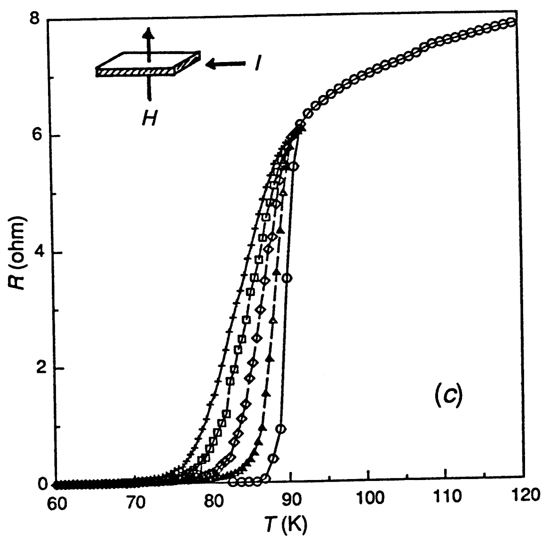

Fig. 1. (*Continued*)

Even though pinning forces are very strong, pinning energies are quite weak since the associated potential extends over a very small range of order ξ, the coherence length. Whether this range is normal or parallel to the vortex core distinguishes between two mechanisms that we observe. We find $\xi_{ab} = 20$ Å and $\xi_c = 2$ Å for our samples. Actual pinning energies are discussed below. They are sufficiently small that thermally activated flux motion is significant.

2. Experimental Results

Resistance versus temperature data obtained in fields up to 7 T on thin films with the field parallel to the surface (and hence the *ab* plane) are shown in Figs 1*a* and 1*b*. In Fig. 1*a* the field is normal to the current and in Fig. 1*b* the field and current are parallel. Results at the same value of applied field are identical for the two current directions. In Fig. 1*c* the field is normal to the film (and hence parallel to the *c*-axis).

Table 1. Broadening mechanisms in high T_c materials and their associated critical temperatures

Location of T_c	Broadening mechanism
(a) $T(R = 0{\cdot}9\ R_n)$	Inhomogeneities
(b) $T(R = 0{\cdot}5\ R_n)$	Inhomogeneities
(c) $T(R = 0)$	Fluctuation enhanced conductivity above T_c
(d) $T_c(B = 0)$	Flux creep at $T < T_c$: (i) barrier independent of T; (ii) barrier depends on T, B

3. Possible Broadening Mechanisms

Various possible definitions for T_c based on the R versus T curves in a field are shown in Table 1. The choice of T_c is dictated by the physical mechanism responsible for broadening the transition. In Table 1 R_n is the normal resistance at $T = T_{c0}$, the temperature at which the resistance begins to drop sharply (92 K). The *actual* resistance at $T = T_{c0}$ is lower than R_n due to the presence of fluctuation conductivity which first becomes apparent at higher temperatures as a gradual drop in R below the linear curve. Thus R_n must be found by extrapolation of the linear high temperature resistance curves to $T = T_{c0}$. Here B is the magnetic flux density present. In case (d) $T_c = T_{c0}$, and hence the dissipation processes giving broadening occur in the superconducting state. In (d) the barrier referred to is the height of the pinning potential well, from which fluxoids must be thermally excited to move and contribute to resistance.

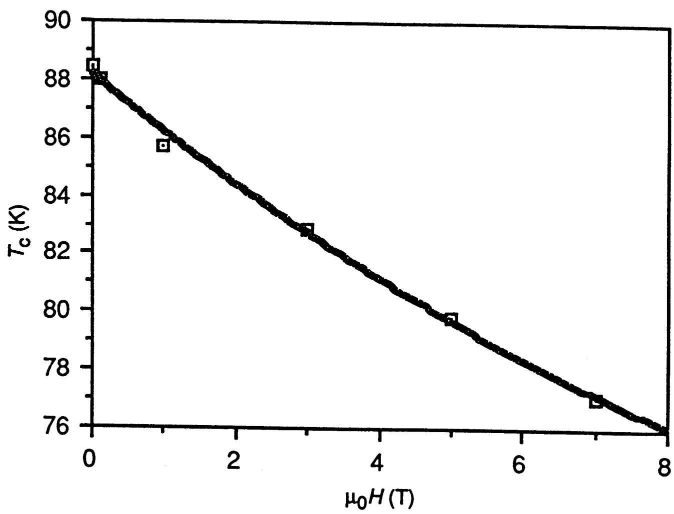

Fig. 2. Critical temperature as a function of the applied field when T_c is defined by T at $R = 0$ (by extrapolation of the linear part of the R versus T plot). The field is parallel to the c-axis.

(a) Model A—Critical Fluctuations

In the presence of a very small coherence length localised fluctuations between normal and superconducting states are more likely to occur. As a result T_c is shifted downwards and conductivity above T_c enhanced (Oh *et al.* 1988). To test this model we use the upper critical fields in the ab plane (H_{c2}^{ab}), and along the c-axis (H_{c2}^{c}), defined in the presence of anisotropy and fluctuations as (Morris *et al.* 1972)

$$H_{c2}^{c} = \frac{\phi_0}{2\pi\mu_0 \xi_{ab}^2(T)}, \qquad H_{c2}^{ab} = \frac{\phi_0}{2\pi\mu_0\, \xi_c(T)\, \xi_{ab}(T)}, \tag{1}$$

with

$$\xi(T) = \frac{\xi_0}{(1-t)^\nu} \quad \text{with} \quad t = \frac{T}{T_c}. \tag{2}$$

In equations (1) ϕ_0 is the quantum of magnetic flux ($h/2e$) and if mean field theory is applicable $\nu = \frac{1}{2}$. Analysis of our data on two films, defining T_c to be $T(R/R_n = 0)$ by extrapolation, gives the results in Fig. 2 for H along the c-axis. Using equations (1) and (2) with $T = T_c(H)$ we find $\nu = 0 \cdot 67 \pm 0 \cdot 04$ and $\xi_{ab} \sim 20$ Å. It is interesting that $0 \cdot 67$ is a well known critical coefficient ([3] XY model (Ma (1976)). In contrast ξ_c is much lower (~2 Å), and the critical coefficient higher. However, the result is less accurate for fields in the ab plane owing to the limited range of $T_c(H)$ in Figs 1a and 1b. An alternative explanation below involving flux motion triggered by fluctuations in localised phase coherence also gives $\nu \sim 0 \cdot 7$ for H parallel to the c-axis.

(b) Models B and C—Intrinsic Flux Motion

In both these models voltage is generated by flux motion due to thermal activation of pinned vortices. Associated with this is an alteration of the local phase difference θ of the wavefunction between two points. If this occurs then moving flux gives a voltage across those points, the same as that across a Josephson junction when flux moves across it, namely

$$V = \phi_0 \frac{1}{2\pi} \frac{d\theta}{dt}. \tag{3}$$

This flux motion is intrinsic in both the models that we now discuss in that it appears to involve pinning energies U and pinning sites that relate to the crystal structure rather than to defects. That is the pinning is a characteristic property of the ideal superconducting material in the high T_c structures. The fields are large enough that flux has penetrated the grains.

Model B—Constant activation energy. Below $R/R_n \sim 0 \cdot 02$ we find that conductivity is thermally activated with an activation energy $U \sim 90$ meV (see Fig. 3). This activation energy is only weakly dependent on magnetic field and apparently independent of temperature. The dependence of U in this model on crystalline orientation is also weak and it is also largely sample independent. Others have measured critical currents versus field (Mannhart *et al.* 1988) and found a similar activation energy. Almost identical activation energies have also been found in bismuth-based high T_c materials (Palstra *et al.* 1988).

Model B ceases to apply at a value of R/R_n shown by the horizontal arrows in Fig. 3. Model C character (see below) applies at higher values of R/R_n. This crossover is very orientation dependent as seen in the plot, but is not field dependent. The ratio U/T at a fixed value of R/R_n in this simply activated model B regime has a similar weak field dependence to U itself. This ratio in conventional models of flux creep depends on the log of the resistance prefactor. This prefactor involves the attempt frequency with which a particular fluxoid tries to escape from its energy well.

The narrow range of low U values and the universality of their character between different samples and even different high T_c materials is a strong indication that these energy barriers are intrinsic. By this we mean that they are a characteristic of the ideal high T_c superconducting material and do not depend as in low T_c materials on the presence of additional defects. The intrinsic model applicable to the low U values in model B can be traced to the short range of the pinning potential defined by the width of the vortex core (~ξ) in directions normal to the applied field. In model C the relevant

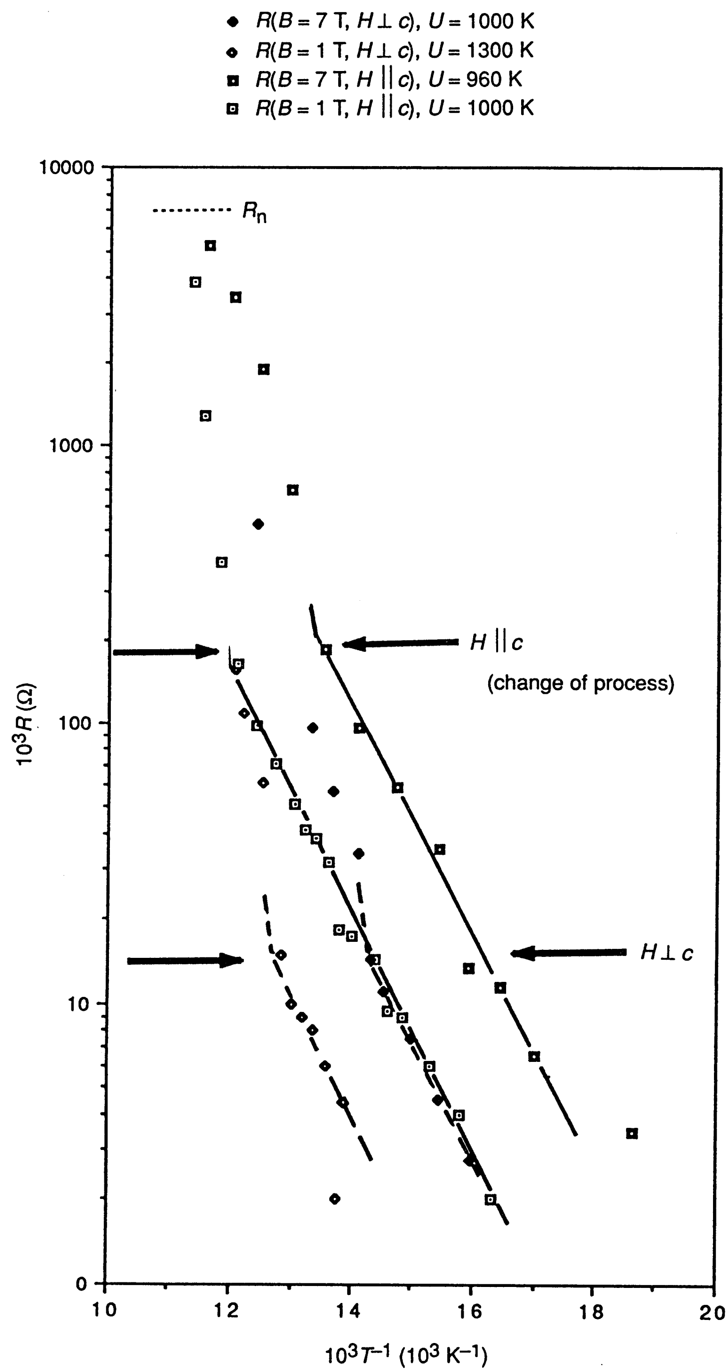

Fig. 3. Log plot of R versus T^{-1} demonstrating activated behaviour below a fixed R value determined only by field direction. Activation energies are also given.

scale that governs the energy barrier for fluctuations is ξ along the vortex. The latter can lead to large anisotropies in U with field direction, since the coherence length is anisotropic, while in this model B there will always be some directions normal to the field for which the larger (ab) correlation length is applicable.

Model C—Variable activation energy. In this model (Tinkham 1988) the activation energy depends on the free energy per unit volume of the vortex lattice ($\propto H_c^2$), with H_c the thermodynamic critical field and a pinning volume. This volume involved in pinning depends on the scale of the flux lattice spacing $a_0 \approx (\phi_0/B)^{1/2}$, relative to the penetration depth λ. In the high T_c materials it does not take very high fields for a_0 to drop below λ. When this occurs the pinning volume depends on the flux lattice spacing normal to the vortex, rather than on ξ^2. The scaling length of the potential along the vortex is ξ (or a small multiple) and the volume that is involved in each flux movement is thus proportional to $\xi\phi_0/B$. Tinkham (1988) has shown that such a potential leads to equivalence to an identical array of thermally 'noisy' Josephson junctions. Then R/R_n is a known function:

$$R/R_n = [I_0(U/2kT)], \tag{4}$$

$$U = KJ_{c0}(1-t)^{3/2}/B, \tag{5}$$

where $K \approx 3$ to 10, I_0 is the zeroth order modified Bessel function, J_{c0} is the critical current at $T=0$ in zero field, and as before $t = T/T_c$.

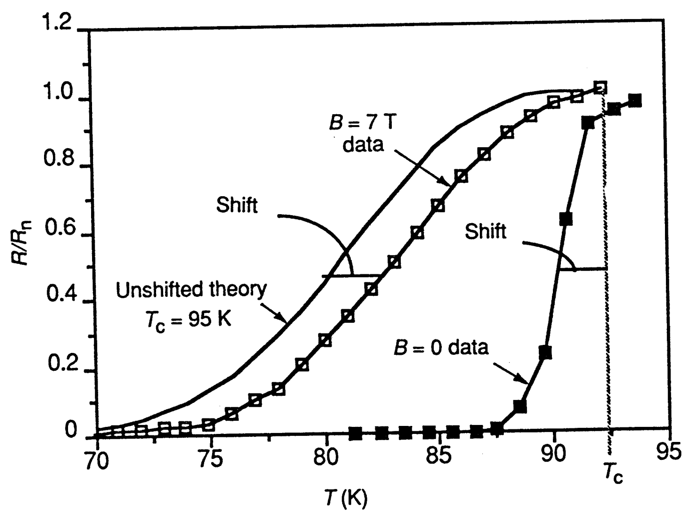

Fig. 4. Theoretical plot of 'best fit' model C predictions to the experimental data for a field of 7 T in the c-direction. The curve must be shifted to match the experimental data by the broadening of the zero field R plot at $R/R_n = 0 \cdot 5$. At very low R/R_n (not shown) this model does not fit the data and model B applies.

A plot of this function chosen to fit our data is shown in Fig. 4 with U as the optimised variable and $1-t$ calculated at each R/R_n. To fit requires a lateral shift of the curve (not done in our case) equivalent to the broadening at $B = 0$ relative to the points at which all curves converge. Such fits give $J_{c0} > 10^6\ \mathrm{A\,cm^{-2}}$ for H in the ab plane. Actual measurement of critical current on this sample gave $\sim 1 \cdot 2 \times 10^6\ \mathrm{A\,cm^{-2}}$. The large anisotropy with field orientation is attributable to anisotropy of the critical current.

From equations (4) and (5) it can be seen that the degree of broadening at fixed R/R_n depends on $B^{2/3}$ and if we define the critical field as that producing a particular threshold value of R/R_n (similar to the procedure in model A), then H_{c2} varies as $(1-t)^{3/2}$ for both H parallel to the c-axis and in the ab plane. This is close to what we found in Section 3*a* for the c-axis direction ($2\nu = 1 \cdot 4$), but not the ab plane.

Our data thus point to two distinct sources of finite resistance below T_c. Model B is more like conventional flux creep and involves a potential that only extends out a distance ξ from the vortex centre, but may act over a long distance along the vortex. Thermally activated flux creep from this potential will be low almost up to T_c, but the onset of thermal fluctuations which disrupt phase coherence over the distance ξ along the vortex also enables flux motion and leads to a rapid rise in resistance at a temperature that drops further below T_c as the field increases. As already noted, model C effects are far more sensitive to the field and field orientation than those in model B.

4. Conclusions

The ability of high T_c materials to carry very large currents is probably due to intrinsic pinning effects rather than pinning by defects. However, another intrinsic process involving random thermally generated fluctuations in phase coherence can cause large resistances to appear in the superconducting state (i.e. below the thermodynamic critical temperature). The energy barrier for these processes is different to that associated with 'normal', simply activated flux creep. It can annul the influence of the 'normal' pinning potential because if the potential barrier preventing localised phase incoherence becomes too weak the vortex is disrupted on a scale much smaller than the length being pinned.

The coherence length (and critical current) in the ab plane is sufficiently large to prevent the onset of the noise component of resistance until T is close to T_c for fields in the ab plane. The much smaller ξ_c leads to much broader transitions for fields in the c-direction. Thus, for high current applications, a high degree of orientation is essential and if achieved should yield excellent performance.

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