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Direct evidence for a change at 50 K in the critical current properties of a $\text{Bi}_{2-x}\text{Pb}_x\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_8$ tape in high magnetic fields

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Abstract

The transport critical current density (J_C) of a monocoil $\text{Bi}_{2-x}\text{Pb}_x\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_8$ silver-sheathed tape has been measured for three sample orientations: (i) $B \parallel c$ -axis, (ii) $J \perp B$, $B \perp c$ -axis, (iii) $J \parallel B$, $B \perp c$ -axis, from 4.2–110 K in fields up to 15 T. For *all three orientations* in high fields, $J_C(B, T) = \alpha(T) \exp(-B/\beta(T))$ where there is a marked change in the temperature dependence of $\alpha(T)$ and $\beta(T)$ at 50 K, such that below 50 K $\alpha(T)$ is much less temperature dependent whereas $\beta(T)$ is much more temperature dependent. We attribute this change to a quasi-2D dislocation mediated Kosterlitz–Thouless transition when the lattice markedly softens. We discuss the evidence that J_C is determined by the average field component parallel to the c -axis (as has been found in epitaxial $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_8$ thin films) and the intergrain connectivity.

1. Introduction

Since their discovery in the late 1980's, high temperature superconductors have appeared to offer many possibilities in scientific and commercial applications. For superconducting power cables, generators and high field magnets (operating at the more economic temperature of liquid nitrogen) the $\text{Bi}_{2-x}\text{Pb}_x\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_8$ (Bi-2223) compound is the most promising. It has high intrinsic values of critical current density (J_C) and can be produced in long lengths in the form of a metal-sheathed tape. The

crystal structure of Bi-2223 is highly anisotropic but the plate-like shape and growth of the grains is such that rolling and annealing the tape naturally aligns them with their c -axis perpendicular to the plane of the tape. Unfortunately the J_C of these Bi-2223 tapes is significantly below that of thin films of the same material. In particular at high temperatures (e.g. 77 K) and in high magnetic fields J_C is presently too low over long lengths for useful applications though recent improvements have led to the development of small prototypes. The reasons for the low measured values and strong field dependence of J_C in Bi-2223 tapes are still not clear. Some of the important factors are considered to be the strength of coupling between grains, the percolation path of the transport current, the types of pinning and the possible phases of the flux line lattice.

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This paper details the measurement of J_C for a monocoire Bi-2223 tape. Data were obtained for three different sample orientations in the temperature range between 2 K and T_C in magnetic fields up to 15 T. Such a complete data set of J_C for a Bi-2223 tape has not previously been presented in the literature. The high field data are analyzed in terms of an exponential field function. Possible explanations in terms of current theories are given and the outstanding issues highlighted.

2. Fabrication

The sample was a 10 mm section cut from a monocoire $\text{Bi}_{2-x}\text{Pb}_x\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_8/10\%$ Ag tape of total length 50 mm. The tape was made using the standard powder-in-tube method [1] and a series of heat treatments with two intermediate pressings. The tape measured 2.8 mm wide by 0.08 mm thick and the average cross-sectional area of the Bi-2223 was 0.0466 mm^2 .

3. Experimental procedure

The sample was mounted in the Durham $J_C(B, T)$ probe, described elsewhere [2]. The voltage taps

were attached with Indium 2 mm apart. The E - J characteristics of the tape were measured for three different orientations of the magnetic field with respect to the tape (in all cases the macroscopic transport current was parallel to the plane of the tape): (i) magnetic field perpendicular to the plane of the tape, called the BPC (B parallel to the c -axis) orientation; (ii) magnetic field parallel to the plane of the tape but perpendicular to the transport current, called the BPAB (B parallel to the ab -plane) orientation, and (iii) magnetic field parallel to the plane of the tape and also to the macroscopic transport current, called the LFF (Lorentz force free) orientation.

The measurements were taken in increasing magnetic fields from 0–15 T. Before and after each change of orientation the critical current of the tape was measured in liquid nitrogen. This was to make sure that the sample had not been damaged during handling or from thermal cycling. No change in the critical current was observed. The critical current density has been calculated from the E - J characteristics using a $2 \mu\text{V cm}^{-1}$ criterion.

4. Experimental results

The J_C data are plotted on log-linear scales in Figs. 1–3. As the field first increases, J_C drops

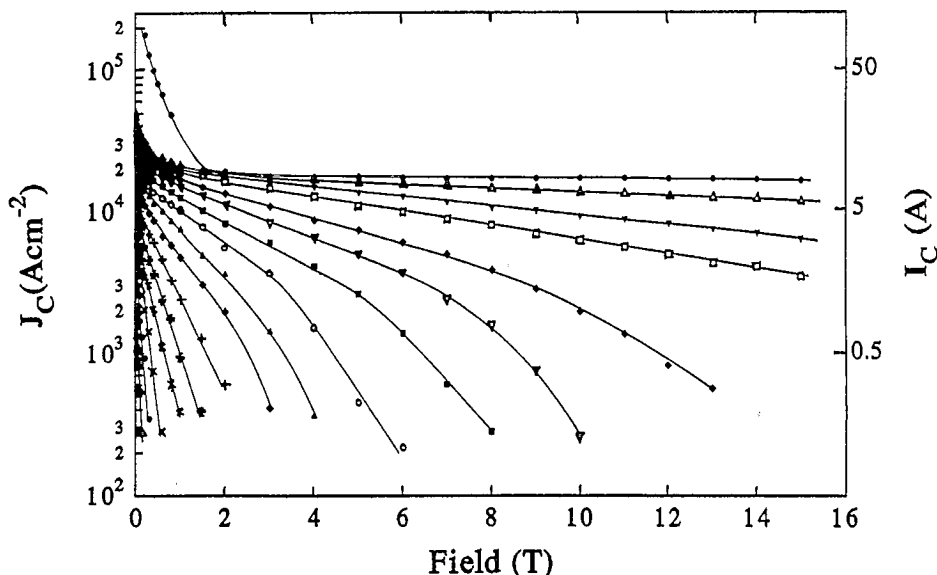


Fig. 1. The critical current density for the B -field parallel to the c -axis (BPC) of the tape on a log-linear scale. The curves are measurements at constant temperatures of (from the top down): 4.2, 10, 20, 30, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90 and 95 K respectively.

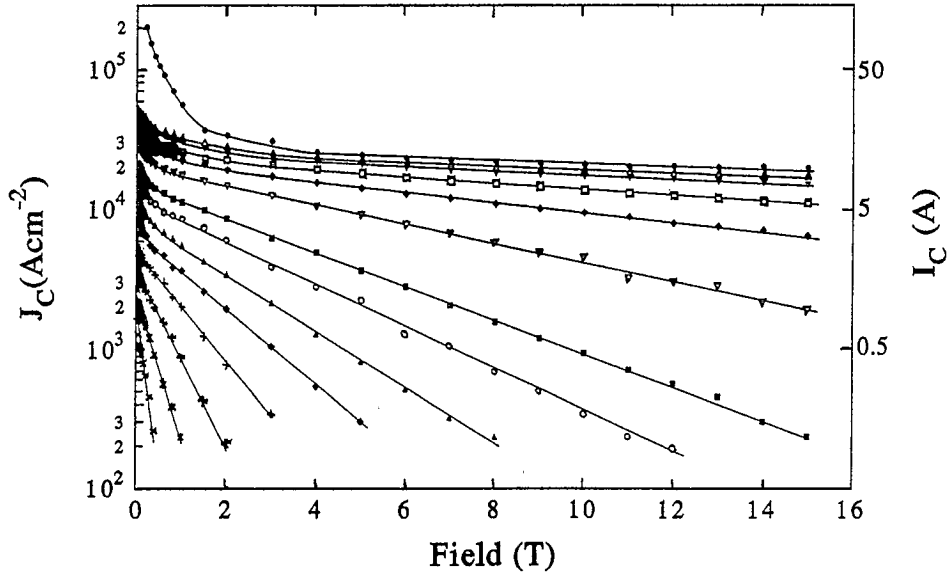


Fig. 2. The critical current density of the tape for the B -field parallel to the surface of the tape and orthogonal to the direction of macroscopic current flow (BPAB) on a log-log scale. The curves are measurements at constant temperatures of (from the top down): 4.2, 10, 20, 30, 40, 50, 60, 65, 70, 75, 80, 85, 90, and 95 K respectively.

precipitously up to a value defined here as $B_{\text{exp}}(T)$. For the BPAB and LFF orientations, $B_{\text{exp}}^{ab}(T)$ is 4–5 T between 4.2 and 30 K, for BPC it is 1.5–2 T and decreases to zero at T_C . The anomalous behaviour in J_C below 10 K at low fields is most probably due to a low T_C (~ 10 K) phase and is discussed elsewhere

[3]. At medium to high fields, at all temperatures for the three orientations, the critical current density decreases exponentially with field. For the BPAB and LFF orientations above $B_{\text{exp}}^{ab}(T)$, the data remains exponential over the entire field range measured. In contrast, for BPC at the highest fields, there

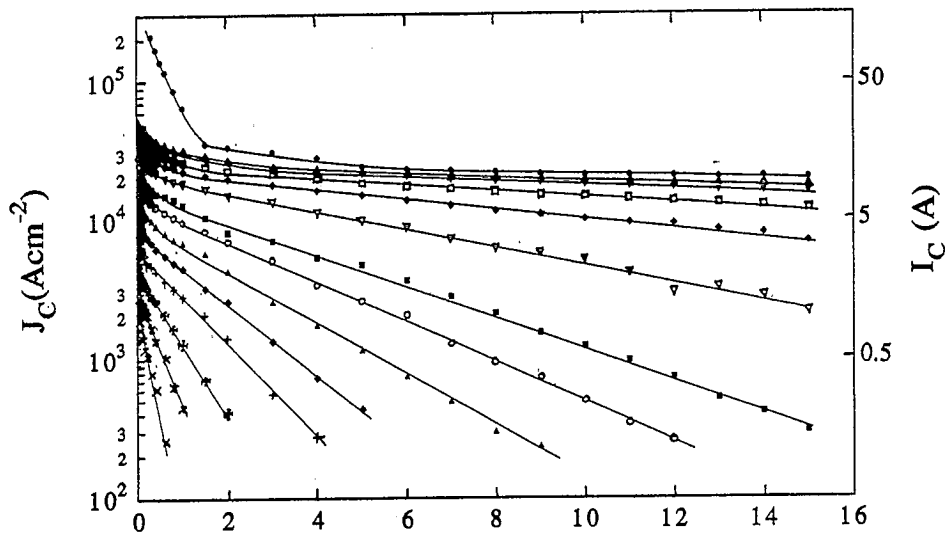


Fig. 3. The critical current density of the tape for the B -field parallel to the surface of the tape and parallel to the direction of macroscopic current flow (LFF) on a log-log scale. The curves are measurements at constant temperatures of (from the top down): 4.2, 10, 20, 30, 40, 50, 60, 65, 70, 75, 80, 85, 90 and 95 K respectively.

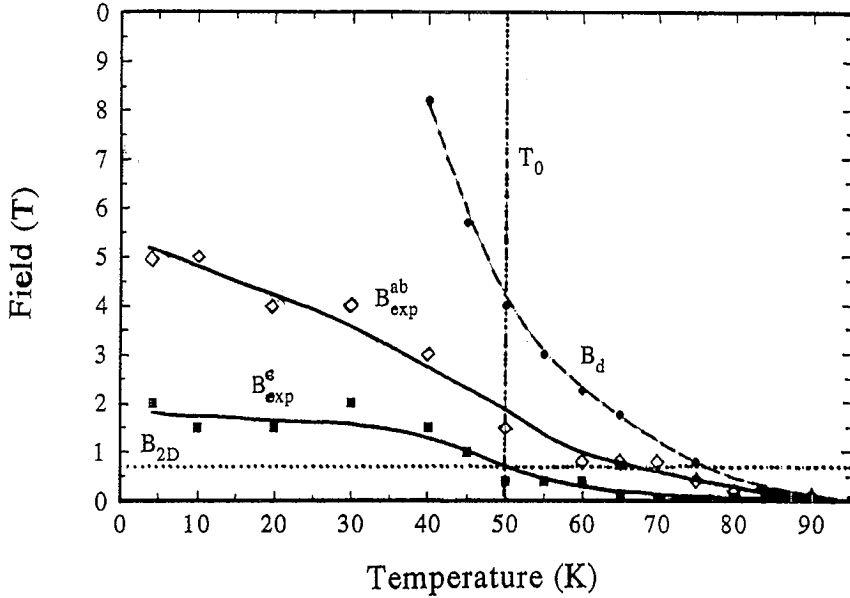


Fig. 4. The B - T phase diagram for the tape. The superscripts c and ab correspond to the BPC and BPAB orientations respectively. B_{exp} is the low field cut-off for exponential form of J_c . B_d is the high field cut-off for the exponential form in the BPC orientation. The temperature T_0 denotes where the temperature dependencies of the parameters α and β change. The field B_{2D} is an estimate for the field above which the 3D vortices change into a stack of pancake vortices.

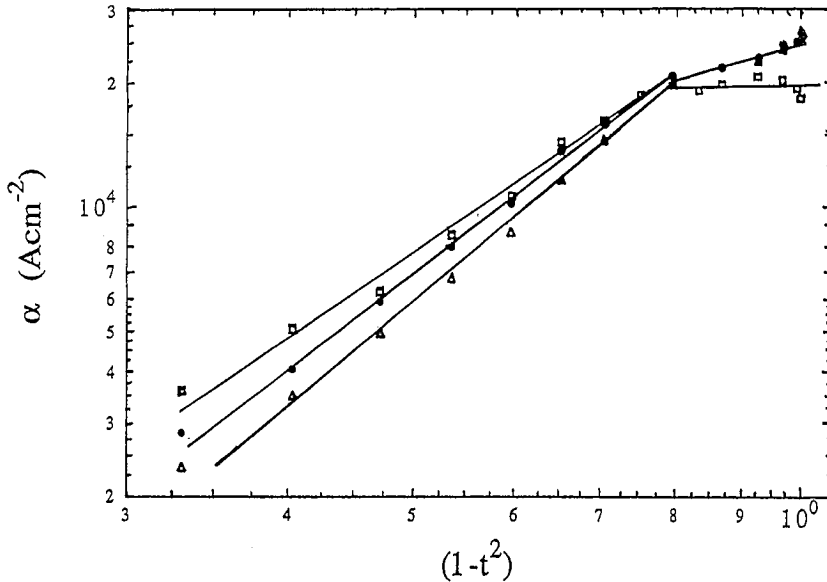


Fig. 5. A plot of $\log_{10}(\alpha(T))$ versus $\log_{10}(1-t^2)$ for the three orientations (\square) B -field parallel to the c -axis (BPC), (\triangle) B -field parallel to the surface of the tape and orthogonal to the direction of macroscopic current flow (BPAB), (\bullet) B -field parallel to the surface of the tape and parallel to the direction of macroscopic current flow (LFF).

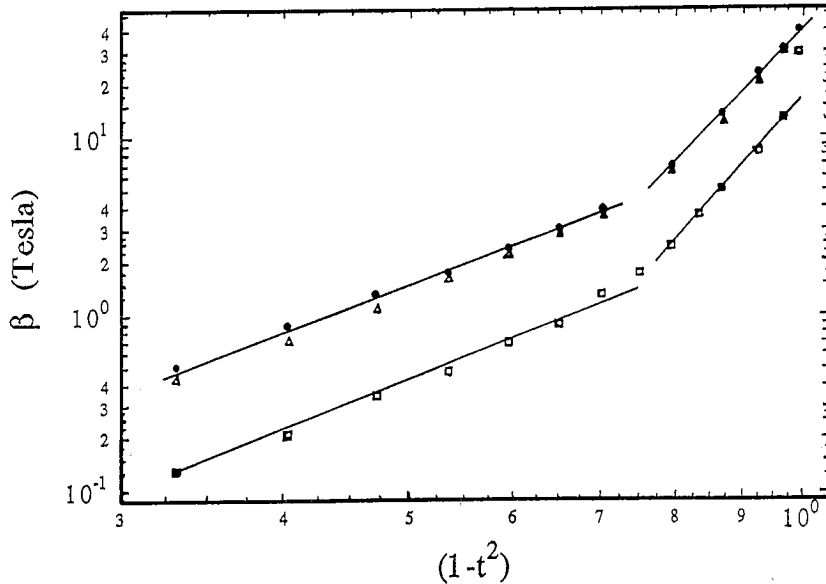


Fig. 6. A plot of $\log_{10}(\beta(T))$ versus $\log_{10}(1-t^2)$ for the three orientations (\square) B -field parallel to the c -axis (BPC), (Δ) B -field parallel to the surface of the tape and orthogonal to the direction of macroscopic current flow (BPAB), (\bullet) B -field parallel to the surface of the tape and parallel to the direction of macroscopic current flow (LFF).

is a rapid decrease in J_C away from the exponential form at a field called here $B_d(T)$. In Fig. 4, the field and temperature dependence of $B_d(T)$ and $B_{exp}(T)$ are shown.

5. Analysis of data

The data have been fitted to the function

$$J_C(B, T) = \alpha(T) \exp(-B/\beta(T)) \quad (1)$$

above the field $B_{exp}^{ab}(T)$ for the BPAB and LFF orientations and between the fields $B_{exp}^c(T)$ and $B_d(T)$ for the BPC orientation. The parameters $\alpha(T)$ and $\beta(T)$ are plotted in Figs. 5 and 6 for the three orientations. In order to describe them more quantitatively they have been plotted on a log–log scale against $(1-t^2)$, where t is the reduced temperature with $T_C = 110$ K. A fit to a $(1-t^2)^n$ dependence has been chosen because of the similar temperature dependence of the important parameters: the coherence length, the magnetic penetration depth, the depairing critical current density and the upper critical field. An attempt to fit the data to a $(1-t)^n$ dependence is also justified but better fits were found with $(1-t^2)^n$. The error in $\alpha(T)$ for each orientation is 5%. The error in $\beta(T)$ is 5% for all orientations and tempera-

tures except at 4.2 and 10 K for the BPC orientation where it is 20%. It should be noted:

(i) There is a significant change in the temperature dependence of both $\alpha(T)$ and $\beta(T)$ at 50 K for all three orientations.

(ii) Above and below 50 K, the temperature dependence of β is the same for all three orientations. Below 50 K the temperature dependence is markedly stronger than above 50 K. $\beta(T)$ for the BPAB and LFF orientations is the same throughout the temperature range and higher than for BPC.

(iii) Above 50 K, $\alpha(T)$ has a weak temperature dependence for the BPAB and LFF orientations and is approximately constant for the BPC orientation. Below 50 K, $\alpha(T)$ for the BPAB orientation falls below the value for the LFF orientation. The $\alpha(T)$ curve for the BPC orientation crosses the BPAB line and lies on or just above the LFF line.

Summarizing the exponential dependence of J_C mathematically we find:

(a) below 50 K,

$$J_C(B, T) = \alpha_{ab}(1-t^2) \exp\left(\frac{-B}{\beta_{ab}(1-t^2)^8}\right)$$

for BPAB, LFF,

(2)

$$J_C(B, T) = \alpha_c \exp\left(\frac{-B}{\beta_c(1-t^2)^8}\right) \quad \text{for BPC,} \quad (3)$$

where $\alpha_{ab} = (2.5 \pm 0.3) \times 10^4$ A cm⁻², $\beta_{ab} = (40 \pm 2)$ T, $\alpha_c = (2.0 \pm 0.2) \times 10^4$ A cm⁻² and $\beta_c = (16 \pm 1)$ T;
(b) above 50 K,

$$J_C(B, T) = \alpha'_{ab}(1-t^2)^{5/2} \exp\left(\frac{-B}{\beta'_{ab}(1-t^2)^3}\right) \quad \text{for BPAB,} \quad (4)$$

$$J_C(B, T) = \alpha''_{ab}(1-t^2)^{5/2} \exp\left(\frac{-B}{\beta''_{ab}(1-t^2)^3}\right) \quad \text{for LFF,} \quad (5)$$

$$J_C(B, T) = \alpha'_c(1-t^2)^2 \exp\left(\frac{-B}{\beta'_c(1-t^2)^3}\right) \quad \text{for BPC,} \quad (6)$$

where $\alpha'_{ab} = (2.9 \pm 0.2) \times 10^4$ A cm⁻², $\beta'_{ab} = (9.3 \pm 0.5)$ T, $\alpha''_{ab} = (2.95 \pm 0.2) \times 10^4$ A cm⁻², $\beta''_{ab} = (9.5 \pm 0.5)$ T, $\alpha'_c = (2.5 \pm 0.3) \times 10^4$ A cm⁻² and $\beta'_c = (3.1 \pm 0.2)$ T. The uncertainty in the exponents of $(1-t^2)$ is $\pm 10\%$.

6. Discussion

6.1. The functional form of J_C

Many transport J_C measurements showing an exponential high field dependence at all temperatures have been made on Bi-based tapes: the 2212 phase [4,5] and the 2223 phase [6–9]. Magnetisation measurements of J_C for Bi-2223 tapes also show the exponential dependence [8,10] but down to much lower fields. In Ref. [8] the J_C of a Bi-2223 tape had an exponential dependence before and after irradiation with heavy ions and markedly increased in magnitude at temperatures above 60 K.

In Bi-2212 [11] and Bi-2223 [12] epitaxial thin films, J_C is exponential up to the highest available fields for all orientations of the film except at the highest temperatures for which a distribution in T_C

throughout the sample is considered responsible [12]. By varying the angle θ that the field makes with the c -axis of the film, it is found that $\beta(T)$ is proportional to $\cos \theta$ [11–13]. The temperature dependence of $\beta(T)$ is also a unique (orientation independent) function. These results can be explained using a two-dimensional theory of intrinsic pinning [13–16]. We can apply this theory to the tape measured here since in a similar way to the epitaxial films, all three orientations have both an exponential field dependence for J_C and the same temperature dependence for the parameter $\beta(T)$. These similarities as well as the crossover in $\alpha(T)$ for the BPC and BPAB orientations have been found for a Ag-doped Bi₂Sr₂Ca₂Cu₃O_x tape [9]. We expect that the grains are not perfectly aligned in the tape, so there will be a distribution of angles between the c -axis and tape surface. A rough estimate of the tape texture can be obtained from the anisotropy in $\beta(T)$. If the average misalignment angle is θ , then for the BPAB orientation the effective field is $B \cos \theta$ and for the BPC orientation it is $B \sin \theta$. From Fig. 6, it can be seen that the ratio of $\beta_{\text{BPC}}(T)$ to $\beta_{\text{BPAB}}(T)$ is approximately constant ($\sim 0.28 \pm 0.02$) throughout the entire temperature range. Therefore, $\beta_{\text{BPC}}(T)/\beta_{\text{BPAB}}(T) = B \sin \theta/B \cos \theta = \tan \theta$ which gives a misalignment angle of $\theta = 16 \pm 2^\circ$. This is similar to the mosaic spread in the grains themselves which is expected to be about 12° [17,18].

We can interpret these results using the railway switch model such that the transport current flows through a fraction of well connected material between grains whilst remaining in the ab -planes. Possible forms of these ab -plane connections are intergrowths between grains or small angle c -axis boundaries [18]. In this case the parameter $\alpha(T)$ broadly characterises the amount of well-connected material in the tape and $\beta(T)$ the field sensitivity of J_C . The analysis above makes the simplifying assumption that locally there are two discrete types of connections across grain boundaries—either fully connected like the thin films or totally unconnected. Considering the coupling across grain-boundaries to determine in detail whether the grains are strongly coupled (thin film like) over a very small fraction of the grain boundaries or less strongly coupled over a larger area of the grain boundaries is beyond the scope of this work. Increases in J_C caused by ion

irradiation in tapes suggests that pinning plays an important role at least above 60 K [8]. Equally, the low absolute values of J_C in tapes compared to epitaxial films points to poor connectivity or coupling between grains. Some of the approaches that may be able to explain the exponential field dependence of J_C are the following.

(i) *Josephson junctions*

The crystal structure may contain intrinsic S–I–S Josephson junctions. For a stack of Josephson coupled superconducting layers in a field parallel to the c -axis Daemen et al. [19] have calculated J_C along the c -axis to be exponential with field for pinning induced disorder. They consider the flux lines to be composed of pancake vortices which when displaced relative to their neighbours in adjacent layers cause a reduction in the local critical current. Applying their theory to the brick-wall model [20], where the current must transfer between grains along the c -axis, for a tape in a perpendicular field they predict a power law dependence of J_C . Such a dependence is not observed in high fields for the tape studied here.

(ii) *Softening of the lattice constants*

Yamafuji et al. [21] show that an exponential field dependence of the form

$$J_C(B, T) = J_{C0} \exp(-B/f(T)) \quad (7)$$

is obtained for a layered superconductor if the tilt modulus softens for high values of k (the wavevector of lattice distortions) such that $C_{44}(k=0)$ is proportional to B . J_{C0} is the zero field critical current density in the absence of thermal fluctuations and $f(T)$ contains information on the pinning potential. For a 3D lattice $C_{44}(0)$ is proportional to B^2 but Yamafuji et al. suggest that a 2D layered structure may produce the required $C_{44}(0) \propto B$ dependence, as has been found for a superconducting transformer [22].

(iii) *Thermal fluctuations of a collectively pinned lattice/vortex glass*

Collective pinning in layered structures and vortex glass theories [23–27] of the flux line lattice do not directly predict the observed field dependence of J_C —assumptions need to be made about the variation of the pinning potential with field and temperature. It

is possible that a distribution in pinning potentials can lead to the observed exponential dependence of J_C . Using the framework of the Kim–Anderson flux creep model and taking a logarithmic potential well structure [28,29] an exponential behaviour of J_C is found of the form

$$J_C(B, T) = J_{C0}(T) \exp(-B \ln(E_0/E_C) \times \ln(J_{C0}/J^*)/f(T)), \quad (8)$$

where $J_{C0}(T)$ is the critical current density in the absence of thermal fluctuations, E_0 and J^* are a characteristic electric field and current density respectively for the material, E_C is an electric field criterion and the function $f(T)$ includes the temperature variation of the average pinning potential.

(iv) *Pair-breaking*

An exponential field dependence for J_C of the form given by Eq. (1) is consistent with some theoretical and experimental work on S–N–S junctions, although the temperature dependencies of $\alpha(T)$ and $\beta(T)$ do not agree with the theoretical description [9,30,31]. This work suggests that the current paths both between the grains and even within the ab -plane may be best considered as S–N–S junctions where pair-breaking is the mechanism limiting J_C . A very detailed knowledge of the electronic structure of the material will be required to critically assess this description.

Without further experimental and theoretical work on the expected variation of and distribution in pinning potentials a true picture of the flux line lattice in Bi-2223 will remain unclear. The correct model will need to explain the B – T phase diagram for the tape including an explanation of the change in $\alpha(T)$ and $\beta(T)$ at 50 K and the curve $B_d(T)$. These factors are discussed next.

6.2. *The change in the temperature dependence of $\alpha(T)$ and $\beta(T)$ at 50 K*

An abrupt change in the functional form of J_C has been observed in other cuprate systems although the behaviour is different to that found in the Bi-2223 tape: Metlushko et al. [32] have observed such a change in $\text{Ti}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_x$ (TSCCO-2223) single

crystals (B parallel to c -axis). Below 40 K J_C was almost field independent but had a strong temperature dependence. Above 40 K J_C had a strong field dependence but its temperature dependence was not as strong. Two possible descriptions for the marked change in temperature dependence will be considered:

(i) *A distribution in T_C s*

We have made preliminary X-ray measurements on similar tapes to that measured here and found the presence of some Bi-2201 (~ 20 K) and Bi-2212 (~ 85 K). Umezawa et al. [33] found traces of the Bi-2212 phase with T_C s from 75–105 K at the grain boundaries in some Bi-2223 tapes. We have suggested elsewhere [3] that there is electromagnetic evidence for second phase material with a T_C near 10 K at the grain boundaries of these tapes. However we do not attribute the change in the temperature dependence of $\alpha(T)$ and $\beta(T)$ at 50 K to a distribution in T_C since (a) there is no known bulk phase with a 50 K transition temperature. (b) Were a distribution of T_C s at about 50 K to be present, one would not expect such a sharply defined change in the temperature dependence of the parameters as observed. Equally, one would not expect the effect of the 50 K material to be field independent as has been observed. (c) Such a description does not naturally explain the Lorentz force dependence of $\alpha(T)$. Below 50 K, $\alpha(T)$ is the same for BPAB and LFF orientations. Above 50 K, there is a clear macroscopic Lorentz force dependence in $\alpha(T)$. Such behaviour indicates a change in the pinning. This leads us to another possible description.

(ii) *A change in the pinning*

A multitude of different flux lattice phases and transitions in highly anisotropic and layered compounds have been suggested in idealised pinning free systems. To address changes in the critical current density, we must also consider the role of pinning (for a good reviews see Refs. [23,34–36]). We suggest that the change in the temperature dependence of $\alpha(T)$ and $\beta(T)$ at 50 K is most easily attributed to a quasi-2D dislocation mediated Kosterlitz–Thouless transition which causes a softening of the flux-line lattice.

It is predicted that in a layered structure, when the pinning length of a correlated flux bundle becomes less than the interlayer spacing s , a vortex parallel to the c -axis will break down into a stack of 2D pancake vortices [37]. This transition is expected to occur at a temperature independent field [24,25] of $B_{2D} \approx \Phi_0/(s^2\Gamma)$ where Φ_0 is the flux quantum and Γ is the anisotropy. Using $s = 18 \text{ \AA}$ and $\Gamma = 960$ [38] for Bi-2223 we get $B_{2D} = 0.7$ T. Above this field the flux line lattice is quasi two-dimensional and there is relatively weak coupling between the layers. We have measured $\alpha(T)$ and $\beta(T)$ in magnetic fields well above B_{2D} , hence we expect the vortices to be of this pancake type. At sufficiently high temperature, Fisher [39] has shown that in a 2D system a Kosterlitz–Thouless melting transition mediated by dislocations can occur such that the shear modulus drops sharply to zero at a *field independent* temperature T_0 over the intermediate field range $0 < B < B_{C2}(T)$. Experimental evidence for this transition has been found in thin films [40,41]. The occurrence of this transition in the Bi-based and Tl-based high T_C superconductors has been discussed before [24,42] where $T_0 \approx 40$ K for Bi-2223 is predicted. Theoretical effort directed at determining how such a transition would effect the critical current density is complicated since at the same point in the (B – T) plane, some properties of the flux line lattice can be 2D-like whereas others can be 3D-like [24]. In principle, the softened quasi-2D lattice could increase J_C because the vortices could be more easily accommodated by the pinning sites or alternatively decrease J_C because of the fluid nature of the flux line lattice. In this work we simply note a marked change in the functional form of J_C at the transition.

6.3. The irreversibility line

The rapid drop of J_C in high fields perpendicular to the tape surface is observed in other data on Bi-2223 [8,9,42]. We expect that the marked decrease in J_C at $B_d(T)$ can be explained by a thermal depinning transition although similar data has been described in terms of a vortex glass to liquid transition [33]. For the BPAB and LFF orientations we expect that the $B_d(T)$ transition occurs at much higher fields than we have used.

6.4. The B – T phase diagram

The critical current properties of the Bi-2223 tape can be summarised in the form of a B – T phase diagram, shown in Fig. 4. J_C can be described by an exponential field function above $B_{\text{exp}}^{ab}(T)$ for the BPAB orientation and between $B_{\text{exp}}^c(T)$ and $B_d(T)$ for the BPC orientation.

$B_{2D}(T)$ gives the field below which one expects a broad 3D lattice and above which a 2D lattice. At T_0 , the lattice softens and there is a marked change in the temperature dependence of $\alpha(T)$ and $\beta(T)$ which we attribute to a quasi-2D Kosterlitz–Thouless transition. Above B_d , there is thermal depinning of the flux line lattice and J_C drops to zero.

7. Conclusions

The conclusions can be summarised as follows:

(i) By analysing the J_C data in terms exponential field function, a marked change in the functional form of the critical current at 50 K has been identified. This change at 50 K is field and orientation independent.

(ii) We suggest that a quasi-2D dislocation mediated Kosterlitz–Thouless melting transition can explain the marked change in the functional form of the critical current density at 50 K.

(iii) We have discussed the evidence that J_C is determined by the average field component parallel to the c -axis.

(iv) We find that when the field is parallel to the c -axis, in high fields J_C drops rapidly towards zero. This irreversibility line is an important constraint for the widespread use of these tapes in applications at liquid nitrogen temperatures.

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