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2011 Supercond. Sci. Technol. 24 032001

(http://iopscience.iop.org/0953-2048/24/3/032001)

IOP Publishing — Superconductor Science and Technology

Supercond. Sci. Technol. **24** (2011) 032001 (5pp) doi:10.1088/0953-2048/24/3/032001

RAPID COMMUNICATION

Evidence that the reversible strain effect on critical current density and flux pinning in $Bi_2Sr_2Ca_2Cu_3O_x$ tapes is caused entirely by the pressure dependence of the critical temperature

D C van der Laan[1,2], J F Douglas[2], C C Clickner[2], T C Stauffer[2], L F Goodrich[2] and H J N van Eck[3]

[1] Department of Physics, University of Colorado, Boulder, CO 80309, USA
[2] National Institute of Standards and Technology, Boulder, CO 80305, USA
[3] FOM-Institute for Plasma Physics Rijnhuizen, Association EURATOM-FOM, Nieuwegein, The Netherlands

E-mail: danko@boulder.nist.gov

Received 13 October 2010, in final form 6 December 2010
Published 23 December 2010
Online at stacks.iop.org/SUST/24/032001

Abstract
It is well known that the critical temperature of cuprate- and iron-based high-temperature superconductors changes with pressure. $YBa_2Cu_3O_{7-\delta}$ coated conductors, as well as $Bi_2Sr_2CaCu_2O_x$ and $Bi_2Sr_2Ca_2Cu_3O_x$ tapes and wires, show a clear reversible effect of strain on their current-carrying capability, but no clear understanding about the origin of this effect has been obtained. For the first time, we present evidence that the pressure dependence of the critical temperature is entirely responsible for a reversible change in critical current and magnetic flux pinning in $Bi_2Sr_2Ca_2Cu_3O_x$ tapes with strain.

1. Introduction

Many, if not all crystalline superconductors, including cuprates and iron-based superconductors show a change in critical temperature (T_c) with pressure [1, 2], where the rate at which T_c changes depends on the crystalline axis along which the pressure is applied [3]. Because of the dependence on T_c, the critical current density (J_c) and magnetic flux pinning strength of cuprates are expected to change reversibly with pressure as well. Although these ceramic superconductors are brittle [4–6], such a reversible strain effect has indeed been measured in many of the cuprate high-temperature superconductors [7–10]. Still no correlation with the pressure dependence of T_c has been made, since it remained unknown how grains and grain boundaries in these multi-granular samples are affected by strain. Such information has become available only recently, which now allows us to correlate the reversible effect of strain on the performance of $Bi_2Sr_2Ca_2Cu_3O_x$ (Bi-2223) tapes with the change in critical temperature with pressure.

2. Experimental details

The effect of strain on I_c and flux pinning was measured on two types of Bi-2223 tapes, which consisted of superconducting filaments that had the *ab*-planes of the grains aligned parallel to the surface of the tape. The first type (type A) was a multi-filamentary tape with a Ag-alloy matrix produced with the powder-in-tube method. The strain dependence of I_c at different fields has been measured previously by use of a brass bending spring, as outlined in [6]. This tape had a relatively low J_c in a self-field of about 167 A mm^{-2} at 77 K (the boiling temperature of liquid nitrogen at sea level) due to a lower degree of alignment between the grains and a low

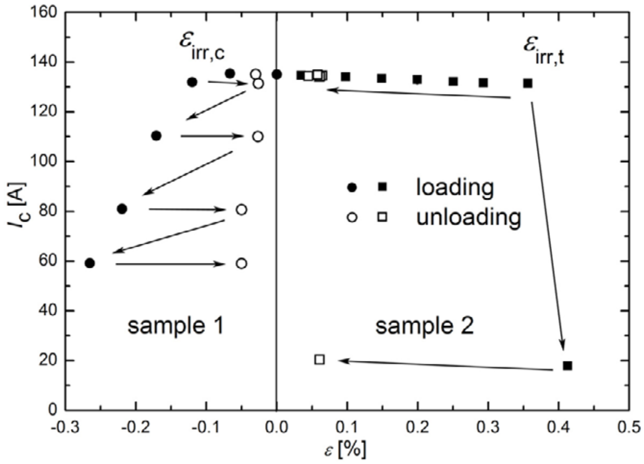

Figure 1. Strain dependence of I_c at 75.9 K in self-field for two samples of type B. Sample 1 was measured under axial compression (round symbols), while sample 2 was measured under axial tension (square symbols). The closed symbols are data points that were taken after the strain had been increased, while the open symbols are data points taken after the strain had been unloaded. The critical current decreases irreversibly when the strain exceeds a compressive strain of $\varepsilon_{irr,c}$, or a tensile strain of $\varepsilon_{irr,t}$.

density of the superconducting material. A detailed analysis of the microstructure can be found in [11]. The second type (type B) was a multi-filamentary tape with Ag-alloy matrix produced with controlled-overpressure sintering. This tape had relatively dense superconducting filaments and a higher degree of grain alignment than is the case in normal-pressure sintered wires [12]. It had a J_c in self-field of about 330 A mm^{-2} at 75.9 K (the boiling temperature of liquid nitrogen in Boulder, Colorado, at an elevation of 1655 m above sea level). Some of the measurements were also performed at 65 K, by pumping on the nitrogen bath. The strain dependence of I_c at different magnetic fields has been measured with the approach outlined in [10]. For values of I_c above 5 A, the critical current (I_c) of the tapes at each strain level was determined within 2% uncertainty for tapes of type A and within 1% for tapes of type B. For both types, I_c was determined within 2.5% uncertainty for values of I_c below 5 A. I_c was determined by use of a four-point measurement at an electric field criterion of 1 μV cm^{-1}. The higher uncertainty at low currents is due to a relatively high current sharing with the Ag-alloy matrix of the tapes.

3. Results and discussion

The critical current of samples of type B changes linearly with strain within the strain range from −0.08% compression (sample 1) to 0.38% tension (sample 2), as shown in figure 1. This linear change is reversible within the absolute measurement uncertainty at the electric field criterion of 1 μV cm^{-1}, which is verified by unloading the strain and measuring I_c at low strain (open symbols), where it fully recovers as long as the strain has not exceeded the irreversible strain limit $\varepsilon_{irr,c}$ under compression and $\varepsilon_{irr,t}$ under tension.

To correlate the reversible effect of strain on I_c in these multi-granular Bi-2223 tapes with the pressure dependence of

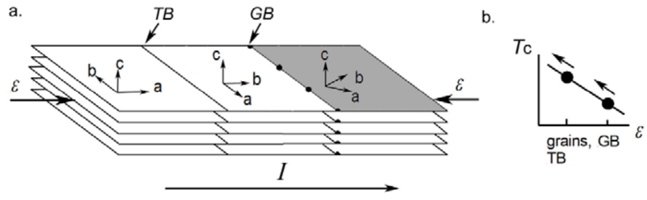

Figure 2. (a) Representation of the microstructure of the current path in Bi-2223 tapes, including twin boundaries within the grains and grain boundaries with dislocations (dots in figure) between the grain on the left (white) and the grain on the right (gray). (b) The change in T_c with strain, showing a linear strain dependence of T_c within the grains and at the grain boundaries. The difference in initial strain state between grains, twin boundaries, and grain boundaries is indicated.

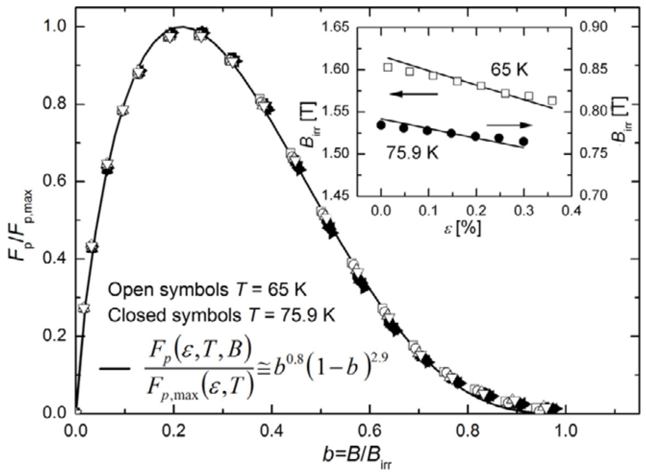

Figure 3. Normalized pinning force versus reduced magnetic field $b = B/B_{irr}$ at 65 and at 75.9 K and for strain values between 0% and 0.38% for a sample of type B. The equation describes the field dependence of the pinning force, where the powers 0.8 and 2.9 follow from the fitted data. The inset shows the strain dependence of B_{irr} obtained from the normalized pinning force at 65 and at 75.9 K, including the fit to the data with equation (3).

T_c, we need to address how strain affects I_c through T_c in grains and at grain boundaries. In Bi-2223 tapes, current flows entirely within the ab-planes of the grains (G), and crosses grain boundaries (GBs) [6, 13] where it is partly obstructed by the lattice distortions caused by dislocations [14] (see figure 2(a)). Twin boundaries (TBs) within the grains, where the lattice is rotated in-plane by 90°, cause a local interchange between the a- and b-axes, but in general do not limit I_c since dislocations are absent [15].

One would expect that grain boundaries in high-temperature superconductors would have a major effect on the strain dependence of I_c. On the contrary, we recently showed in thin film YBCO [001]-tilt grain boundaries [16] and in meandering YBCO grain boundaries in coated conductors [17] that the mechanisms through which strain changes I_c are identical for grains and grain boundaries. Only the initial lattice strain state can be different, where dislocations at grain boundaries introduce a relatively large amount of tensile strain.

A linear increase in T_c with pressure has been measured in Bi-2212 crystals and Bi-2223 whiskers, when uniaxial strain

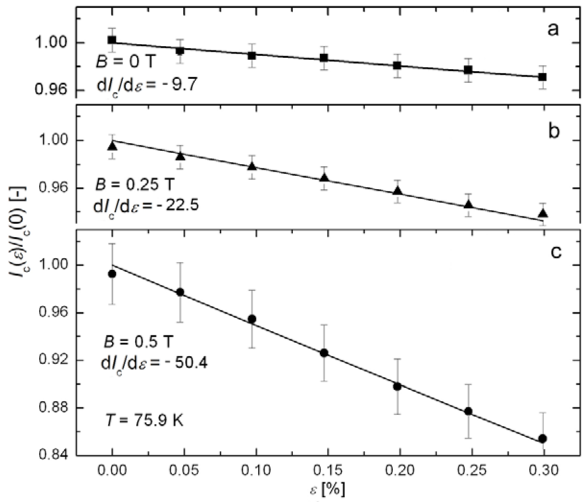

Figure 4. Normalized I_c as a function of strain for a sample of type B at 75.9 K at (a) 0 T, (b) 0.25 T, and (c) 0.5 T. The measured I_c has been normalized to I_c according to equation (2) at zero strain. Only the strain dependence of I_c within the reversible strain range is shown.

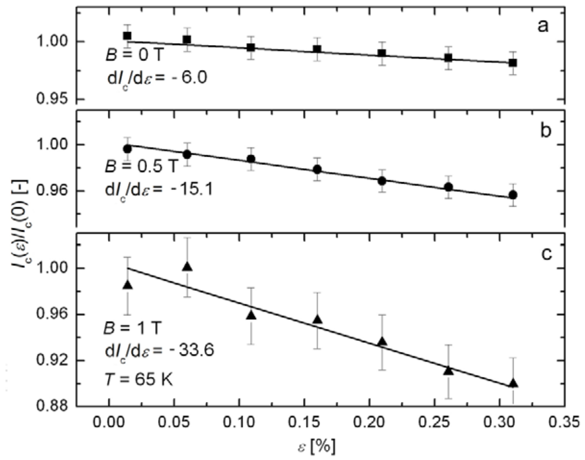

Figure 5. Normalized I_c as a function of strain for a sample of type B at 65 K at (a) 0 T, (b) 0.5 T, and (c) 1 T. The measured I_c has been normalized to I_c according to equation (2) at zero strain. Only the strain dependence of I_c within the reversible strain range is shown.

is applied along the *a*- or *b*-axis [18–20]. The fact that the angle at which strain is applied within the *ab*-planes does not influence the change in T_c has important implications for the strain dependence of T_c in Bi-2223 and Bi-2212 tapes and wires. First, twin boundaries within the grains should not influence the strain dependence of T_c. Second, since transport current in Bi-2223 tapes is confined to the *ab*-planes, we expect that the relative change of T_c with strain is the same for grains and grain boundaries, even though their initial T_c may be different due to the large amount of tensile strain at grain boundaries (see figure 2(b)). The strain dependence of T_c in Bi-2223 tapes should therefore not be influenced by the presence of grain boundaries in the current path, or by the angle at which grains are connected. This implies that the relative change in T_c and possibly I_c with strain is independent of the average grain alignment and thus the quality of the Bi-2223 tape.

A change in T_c with strain will cause a change in I_c through its dependence on temperature, which not far below T_c can be described by [21]:

$$I_c(\varepsilon, T) = I_c(0, 0)\left(1 - \frac{T}{T_c(\varepsilon)}\right)^{1.5}. \qquad (1)$$

The power of 1.5 follows directly from measurements of I_c versus temperature (not shown here). According to this equation, the strain sensitivity of I_c increases when the temperature is raised towards T_c.

The temperature below which a superconducting current can be sustained (which is equal to T_c in the absence of a magnetic field) decreases when a magnetic field is applied. This effective critical temperature is the irreversibility temperature (T_{irr}). The strain, temperature, and magnetic field dependence of I_c can be described by equation (1) when $T_c(\varepsilon)$ is replaced by $T_{irr}(\varepsilon, B)$:

$$I_c(\varepsilon, T, B) = I_c(0, 0, B)\left(1 - \frac{T}{T_{irr}(\varepsilon, B)}\right)^{1.5}, \qquad (2)$$

where $I_c(0, 0, B)$ is a field-dependent fitting function. The strain and magnetic field dependence of T_{irr} is obtained by inverting the temperature dependence of the irreversibility field (B_{irr}; the magnetic field above which a supercurrent can no longer be sustained due to flux flow [22]):

$$B_{irr}(\varepsilon, T) = B_0\left(\frac{T_c(\varepsilon)}{T} - 1\right)^{\frac{1}{d}}, \qquad (3a)$$

which results in

$$T_{irr}(\varepsilon, B) = \frac{T_c(\varepsilon)}{(\frac{B}{B_0})^d + 1}, \qquad (3b)$$

where B_0 and d are fitting parameters. In equation (3*a*), $B_{irr}(\varepsilon, T)$ is defined as the temperature and strain-dependent magnetic field at which flux flow occurs when the macroscopic pinning force ($F_p = I_c \times B$) vanishes. Its value can be obtained by plotting F_p, normalized to its maximum value ($F_{p,max}$), against the reduced magnetic field B/B_{irr} [9, 23, 24], as presented in figure 3 for data taken at 65 and at 75.9 K. Included in the figure is an expression that is often used to describe the magnetic field dependence of the pinning force, although this expression is not used to obtain $B_{irr}(\varepsilon, T)$. The strain dependence of $B_{irr}(\varepsilon)$ at 65 and 75.9 K for a sample of type B, which follows from the normalized pinning force, is presented in the inset of figure 3. The irreversibility field indeed decreases linearly with tensile strain by about -0.17 T/% at 65 K and by about -0.11 T/% at 75.9 K. By fitting the strain dependence of B_{irr} with equation (3*a*), and applying $T_c(\varepsilon) = T_c(0) + a\varepsilon$ (consistent with [18–20]), we obtain the values of parameters $B_0 = 3.17$ and $d = 0.63$ for samples of type A and B. T_c at zero strain, $T_c(0) = 107.2 \pm 0.3$ K, and the slope of the T_c versus strain dependence, $a = -2.89$ K/%, are derived from fitting the strain dependence of B_{irr} and I_c (see below). Note that the slope of $T_c(\varepsilon)$, defined by parameter a, is close to that of -2.2 K/% reported for Bi-2223 whiskers in [18].

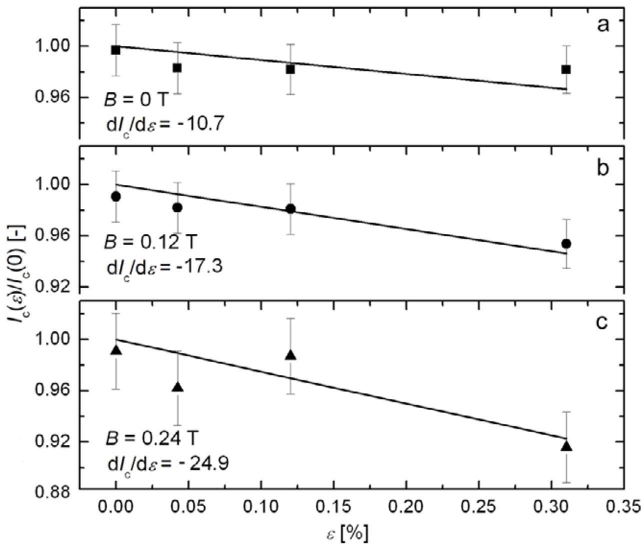

Figure 6. Normalized I_c as a function of strain for a sample of type A at 77 K at (a) 0 T, (b) 0.12 T, and (c) 0.24 T. The measured I_c has been normalized to I_c according to equation (2) at zero strain. Only the strain dependence of I_c within the reversible strain range is shown.

The strain dependence of I_c as a function of temperature and magnetic field in the reversible strain range of Bi-2223 tapes can now be determined with equations (2) and (3). We present the strain dependence of $I_c(\varepsilon, T, B)/I_c(0, T, B)$ for a sample of type B in figure 4 for different magnetic fields applied normal to the tape plane at 75.9 K, and in figure 5 for data taken at 65 K. Included in the figures is a fit to the data with equation (2). The normalization of I_c removes the fitting parameters $I_c(0, T, B)$ from equation (2). The change in I_c with strain increases with applied magnetic field from about -9.7 at self-field to about -22.5 at 0.25 T and about -50.4 at 0.5 T. A similar increase in the strain dependence of I_c is measured at 65 K, although, as expected, the slope at self-field is lower than that at 75.9 K.

As mentioned above, the reversible strain dependence of I_c in Bi-2223 is not expected to be influenced by the presence of grain boundaries and thus the quality (grain alignment and overall I_c) of the tape. This is confirmed by fitting the strain dependence of I_c for a sample of type A (which has a lower degree of grain alignment) with equation (2) for different magnetic fields at 77 K (figure 6).

A reversible strain effect where I_c decreases linearly with strain has been measured in Bi-2212 wires and tapes as well [4]. This is not surprising since T_c in this material also changes linearly with uniaxial pressure that is applied along the a- and b-axes, similar to Bi-2223 [18, 19]. It becomes more difficult to correlate the reversible change in I_c with the pressure dependence of T_c in materials where the direction in which T_c changes with pressure depends on the angle at which strain is applied within the ab-plane. In YBCO, T_c increase linearly with pressure applied along the b-axis, while it decreases linearly with pressure applied along the a-axis [3]. Since a transport current in YBCO is confined within the ab-planes, twin boundaries within the grains will affect the strain dependence of I_c in YBCO. A transport current will pass through areas where T_c increases with compressive strain (where strain is aligned with the b-axis), and through areas where T_c decreases (where strain is aligned with the a-axis). Thus, a strain state exists at which a maximum in overall T_c and I_c is reached. Both T_c and I_c will decrease when the strain state is moved away from this optimum value by applying either compressive or tensile strain. Such behavior has indeed been measured in YBCO coated conductors [7] and YBCO single-crystalline thin films [16], where the strain dependence of I_c is almost parabolic.

4. Conclusions

Thanks to new insight into how strain affects the local properties of high-temperature superconductors, we were able to relate the strain-induced reversible change in critical current and flux pinning in $Bi_2Sr_2Ca_2Cu_3O_x$ tapes to the pressure dependence of its critical temperature. This finding will allow us to better understand the reversible strain effect in YBCO and possibly other cuprate superconductors.

Acknowledgments

The authors thank Sumitomo Electric USA Inc. for providing some of the samples. This work was supported in part by the US Department of Energy, Office of Electricity Delivery and Energy Reliability. This work was partially supported by NIST and is not subject to US copyright.

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