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Thermally assisted flux flow and individual vortex pinning in $Bi_2Sr_2Ca_2Cu_3O_{10}$ single crystals grown by the traveling solvent floating zone technique

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Magnetoresisitivity and critical current density J_c as a function of temperature and field are studied for $Bi_2Sr_2Ca_2Cu_3O_{10}$ single crystals grown using the traveling solvent floating zone technique. Below a characteristic field B^*, J_c as a function of field exhibits a field-independent plateau associated with thermally activated pinning of individual vortices. Analysis of resistive transition broadening revealed that thermally activated flux flow is found to be responsible for the resistivity contribution in the vicinity of T_c. The activation energy U_0 is 800 K in low field, scales as $B^{-1/6}$ for $B<2$ T and drops to 200 K with $B^{-1/2}$ for $B>2$ T. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1855531]

I. INTRODUCTION

Although Y–Ba–Cu–O (YBCO) coated conductors exhibit superior superconducting performance over Bi–Sr–Ca–Cu–O (BSCCO) superconductors (Bi2212 and Bi2223 phases), the BSCCO materials are still believed to be the candidates with the most potential for practical applications at both 77 K (to carry large superconducting current) and at liquid helium temperature (to generate high magnetic fields). The disadvantage of BSCCO is its weak flux pinning at elevated temperatures resulting in a significant drop in critical current density as magnetic field increases. The intrinsic flux pinning properties of YBCO and Bi2212 have been extensively studied on high quality single crystal samples.[1] However, little is known about the intrinsic flux pinning in Bi2223 superconductors as single crystal samples are extremely difficult to grow.

In terms of the J_c field dependence of YBCO and BSCCO, it has been found that there is a characteristic field B^*, separating the field independent region in the J_c from the region of decreasing J_c as a function of magnetic field.[2–4] The origin of the B^* is still unclear in both YBCO and BSCCO. Matching effects and the thermal activated depinning of individual vortices have been proposed to be responsible for the B^* in YBCO and Bi2223 Ag sheathed tapes.[3–5] Also, the pinning potential U_0 in Bi2212 was found to be weakly dependent on magnetic field, while U_0 strongly decreases with fields in MgB_2, which is one of the candidates proposed to replace conventional superconductors.[6] In this paper, we report on our studies on the origin of B^*, the resistive transition broadening, and the intrinsic thermal activation energy U_0, based on high quality Bi2223 single crystal samples successfully grown using the traveling solvent floating zone technique.

II. EXPERIMENT

The Bi2223 crystals used in this study were grown using the traveling solvent floating zone technique. The crystal growth was performed in a Crystal System Inc. infrared radiation furnace equipped with four 300 W halogen lamps. Prior to the crystal growth a high density feed rod was obtained by premelting the rod at a rapid rate of 25 mm/h in air. It was found that Bi2223 crystals with sizes up to $10 \times 6 \times 0.5$ mm^3 can be obtained using a very slow growth rate of 0.04 mm/h and in a mixed gas flow of 20% Ar and 80% O_2. A detailed description of the crystal growth and

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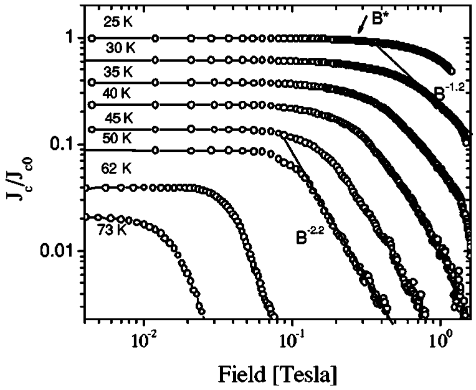

FIG. 1. Normalized critical current density as a function of magnetic field measured at different temperatures. Straight lines are linear fitting of $J_c \sim B^{-n}$.

structure characterization has been reported elsewhere.[7] Optically flat pieces were obtained by cleaving the large crystals and then they were shaped into a rectangular bar using a focused ion beam technique for transport and magnetic measurements. Bi2223 crystal used in this study has a sharp transition and a T_c of 103 K. Magnetic hysteresis loops were measured using vibrating sample magnetometry in field up to 1.75 T over a wide temperature range from 4.2 K up to 80 K. The temperature dependence of the resistivity was measured by a standard four probe method using a magnetic property measurement system in fields up to 5 T with the field perpendicular to the *ab* plane.

III. RESULTS AND DISCUSSIONS

The critical current density J_c was calculated from magnetic hysteresis loops measured at different temperatures using the extend Bean model, $J_c = 20\,\Delta M/[a(1-a/3b)]$, with $a<b$ where a and b are the sample dimensions. The field dependence of the normalized J_c measured at different temperatures with the field parallel to the c axis of the Bi2223 crystal is shown in Fig. 1. It can be clearly seen that the J_c has a field independent plateau below a characteristic field $B^*(T)$. Below B^*, J_c is independent of field, while J_c decreases with field above B^*. We plotted B^* as a function of reduced temperature t (T/T_c) as shown in Fig. 2. It was found that B^* vs T/T_c can be fitted by $B^*(t)=B^*(0)\exp(-qt)$ where $q=10$. This formula was found to closely describe the thermally activated depinning process in different high T_c superconductors and has been shown to be even more suitable for describing depinning in highly anisotropic Bi–Sr–Ca–Cu–O (BSCCO) superconductors.[8,9]

It should be pointed out that the values of B^* are ten times larger than those for both Y123 films[2] and Bi2223 tapes[5] over a wide temperature range. These values are surprisingly high, but the reasons are unclear, requiring a detailed investigation. For Y123 films, it has been reported that the values of B^* are proportional to the density of linear defects present in the films. The higher the density of linear defects, the larger the B^*. Furthermore, the J_c (at $B>B^*$) of the films with a high density of linear defects drops much more quickly as fields increase ($J_c \sim B^{-1}$) than in films with a low density of linear defects where J_c scales as $B^{-1/2}$. For our

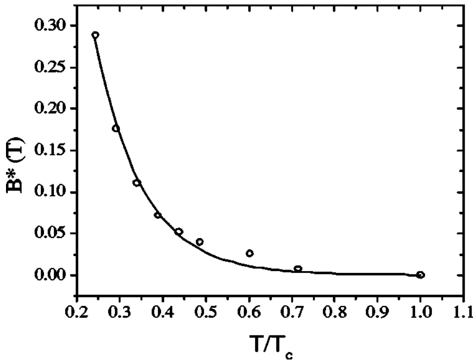

FIG. 2. B^* as a function of reduced temperature.

Bi2223 single crystals, we found that for $B>B^*$, $Jc \propto B^{-n}$ ($n=1.2$ at 30 K and $n>2$ for $T>50$ K), suggesting collective pinning at low temperatures.[4]

The rather high value of q observed in Bi2223 single crystal is believed to be due to the surprisingly large values of B^* and also likely to be due to the differences between the pinning of individual vortices in the vicinity of B^* and the collective pinning close to B_{irr}, as suggested for the case of Bi2223 tapes.[5] When vortex-vortex interactions become important near B^*, the pinning of individual vortices weakens to allow a crossover to collective pinning, and vortices become very sensitive to thermal activation. The exponential $B^*(t)$ dependence of Bi2223 single crystal implies that B^* could depend on the onset of thermally activated depinning of individually pinned vortices, as predicated for the case of linear defects that are being commonly present in pulsed laser deposition Y123 thin films[4] and reported for Ag-sheathed Bi2223 tapes.[5]

Thermally activated flux flow is also manifested in the broadening of superconducting transitions in the Bi2223 single crystals. The broadening of the resistive transition in a magnetic field for layered superconductors is interpreted in terms of a dissipation of energy caused by the motion of vortices.[10] The resistance in the broadened region is caused by the creep of vortices so that the ρ (T) dependence is of the thermally activated type described by the equation $\rho(T,B) = \rho_0 \exp[-U_0/k_B T]$, where U_0 is the flux-flow activation energy, which can be obtained from the slope of the linear part

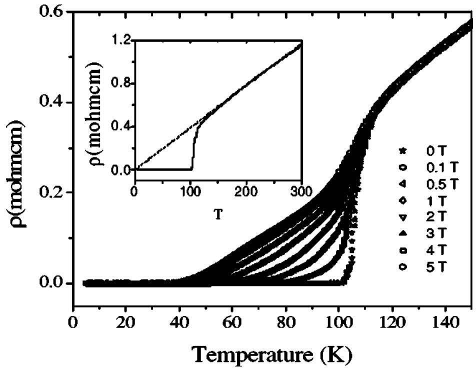

FIG. 3. Temperature dependence of the electrical resistivity of a Bi2223 single crystal in different magnetic fields parallel to the c axis. Inset: the zero-field resistivity up to room temperature.

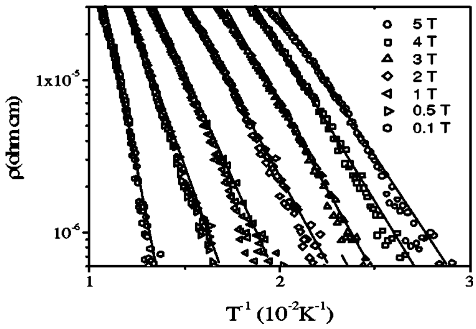

FIG. 4. Arrhenius plot of the electrical resistivity of a Bi2223 single crystal for all measured fields parallel to the *c* axis. The activation energy U_0 is given by the slopes from a linear fitting.

of an Arrhenius plot. The U_0 can be deduced only from the limited temperature intervals below T_c, where the data from the Arrhenius plot of $\rho(T)$ yields a straight line.

In Fig. 3, we show the temperature dependence of the electrical resistivity $\rho(T)$ for zero field and seven fields perpendicular to the *ab* plane using a dc current of 1 mA. Large magnetoresistance was present down to relatively low temperatures. With the increase of magnetic field, the resistivity and T_{c0} gradually increase and decrease, respectively. The Bi2223 crystal shows room-temperature resistivity of about 1 mΩ cm with a T_{c0} of 103 K and transition width ΔT_c of 3 K. The sharpness of the transition with zero residual resistance determined by extrapolating to zero temperature (see inset) indicates that the sample have a high crystallinity and chemical purity.

In Fig. 4, we plot the data for field parallel to the *c* axis as log ρ vs T^{-1}. The thermally activated behavior of the resistance is immediately apparent. The slope of the curve is the activation energy U_0. The best fit of the experimental data yields values of the activation energy ranging from $U_0/k_B = 800$ K in the low field of 0.1 T down to 200 K in 5 T, as shown in Fig. 5. It has been reported that for Bi2212 crystals the activation energy exhibits different power-law dependences on magnetic field, $U_0(B) \sim B^{-n}$, with $n = 1/2$ for $B < 5$ T and $n = 1/6$ for $B > 5$ T in the case where the field is parallel to the *c* axis. Figure 5 shows the magnetic field dependence (up to 5 T) of the activation energy U_0 of Bi2212 (data were extracted from Ref. 1) and the Bi2223 single crystals used in this study. We can see that the U_0 for both samples is comparable for a field of 0.1 T. However, the values of U_0 for Bi2223 drop much more quickly than that of Bi2212 with J_c scales as $B^{-1/6}$ for $B < 2$ T and then decreasing slowly with $B^{-1/2}$ for $B > 2$ T. The value of U_0 in high field for the Bi2223 crystal is only 200 K, two times smaller than that of Bi2212. This indicates that the Bi2223 has a very much weaker intrinsic pinning than that of Bi2212. However,

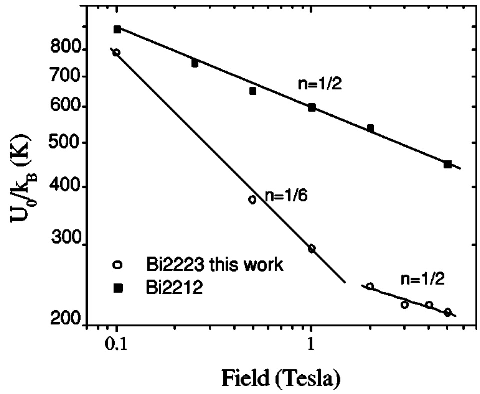

FIG. 5. Magnetic field dependence of the activation energy U_0 of Bi2223 single crystals in fields parallel to the *c* axis. The linear portions of the data suggest a power law $U_0 \sim B^{-n}$. The data for Bi2212 were extracted from Ref. 1.

it should be noted that the relatively large U_0 reported for Bi2212 crystals also exhibited relatively large values of residual resistivity at zero temperature, a manifestation of poor quality that is probably due to either crystal imperfection or chemical impurities. The small value of U_0 of our high quality Bi2223 single crystals should be originated from a different pinning mechanism, probably from the intrinsic weak pinning in the Bi2223 material.

IV. CONCLUSIONS

In summary, for Bi2223 single crystals, below a characteristic field B^*, J_c as a function of applied field exhibits a field-independent plateau due to thermally activated pinning of individual vortices. Thermally activated flux flow is found to be responsible for resistive transition broadening. The activation energy U_0 is 800 K in low field, varies with $B^{-1/6}$ for $B < 2$ T and drops to 200 K with $B^{-1/2}$ for $B > 2$ T.

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