Critical-current characteristics of c-axis-oriented $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ silver-sheathed tapes from 10 K to T_{c0}

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The dependence of the transport critical-current density on an applied magnetic field and temperature of a high-J_c $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ silver-sheathed tape has been measured in the range from 10 to 110 K. It is found that the transport critical current follows the relation $J_c = J_{c0}(1 - aT + bT^2)$. For $T < 40$ K, $b = 0$, while for $T > 40$ K, $b > 0$. J_c and the applied field follow a power-law relation $J_c \propto B^{-\alpha}$ $(\alpha \approx 0.3)$ for $T < 40$ K and an exponential-law $J_c \propto \exp(-\beta B)$ for $T > 65$ K. For 40 K $< T <$ 65 K, there is a transition field for $J_c(B,T)$. This represents a transition of the above two relations for $J_c(B)$. The experimental results can be explained within the framework of the flux-creep model in terms of different potential-barrier forms. The limitation of J_c from 10 K to T_{c0} seems to be attributed to the flux creep for high-J_c textured Bi(2223) Ag-sheathed tapes. The flux lattice seems to experience a transition that is similar to the flux-lattice melting in this material in both applied-magnetic-field orientations near 40 K.

I. INTRODUCTION

It is known that the critical current of high-T_c superconductors is influenced by the weak links among the grain boundaries and the intragranular flux pinning. In order to overcome the influence of the weak link, some particular fabrication techniques such as melt texture growth, quench melt growth, and powder melt process have been successfully developed.[1–3] Except for these techniques, the powder-in-tube method appears to be the most effective technique for application on the industrial scale. The Bi-system oxide superconductor is technologically important because a relatively high transport critical-current density, $J_c \sim 10^8 - 10^9$ A/m^2, can be obtained in polycrystalline samples such as Ag-sheathed tapes.[4,5] Recently a high J_c value of 6.9×10^4 A/cm^2 has been reported for Bi(2223)/Ag tapes.[6] However, some questions remain unclear, such as what is the mechanism controlling J_c in Bi(2223)/Ag tapes and does the increase of J_c only come from the improvement of the grain coupling or is the J_c determined completely by the flux pinning?

The present investigation was undertaken to study the dependence of the critical-current density of a high-J_c textured Bi(2223)/Ag tape on the temperature, magnetic field, and field orientation to provide a more complete picture of the complex behavior from 10 K to T_{c0}.

II. EXPERIMENTAL TECHNIQUE

The Bi(2223)/Ag tapes were prepared by the powder-in-tube technique. Oxide powder with a nominal composition of $Bi_{1.8}Pb_{0.4}Sr_{2.0}Ca_{2.2}Cu_3O_x$ was produced by codecomposition of metal nitrates. The oxide powders were then packed into a silver tube with 4 mm outer and 2.4 mm inner diameters. The tape 4 mm wide and 0.2 mm thick was obtained using conventional deformation techniques. The samples were heated at 840 °C in air for 200 h with two intermediate room-temperature pressings. The final thickness of superconducting core is about 45 μm.

Transport J_c measurements were performed by a standard four-probe method using a dc scanning power to eliminate heating effects in the temperature range from 10 to 110 K obtained by means of Cryogenic Refrigeration equipment in an applied magnetic field up to 1 T. An iron-doped gold vs Chromel thermocouple with $a \pm 0.1$ K accuracy was used to measure the temperature of the sample. An electric-field criterion of 10^{-4} v/m was chosen to define J_c. The magnetic field was aligned perpendicular to the current direction and both parallel and perpendicular to the tape surface.

III. RESULTS AND DISCUSSION

The temperature dependence of J_c in an applied magnetic field from 0 to 1 T parallel to the tape surface is shown in Fig. 1. The J_c of the sample shows a linear and a quadratic curvilinear decay with increasing temperature below 40 K and over 40 K, respectively. Figure 2 shows the temperature dependence of J_c in an applied magnetic field aligned perpendicular to the tape surface. It is similar to Fig. 1. For $T<40$ K, the J_c of the sample shows a linear decrease with increase of temperature; however, for $T>40$ K, the J_c manifests a nonlinear decrease with increase of temperature.

The determining factor of transport critical current in polycrystalline high-temperature superconductors is controversial at the present time.[7,8] To clarify if the weak links among grain boundaries still dominate the transport critical current, we have measured the J_c field dependence with increasing and decreasing fields. It is found that $J_c(B)$ is basically reversible, which provides evidence that the effect of the weak links in the present sample is negligible. Our experimental results of temperature dependence of J_c can be accounted for within the framework of the Anderson-Kim flux-creep model[9] and by considering different dependences of the pinning potential $U(t,B,J)$ on J. According to this model, $J_c(t)$ at low temperatures ($t=T/T_c \ll 1$) is given by[10]

$$J_c(B,t)=J_c(B,0)[1-a(B)t-bt^2] , \quad (1)$$

where the linear term is determined from the kinetics of the flux creep and the coefficient b in Eq. (1) is derived

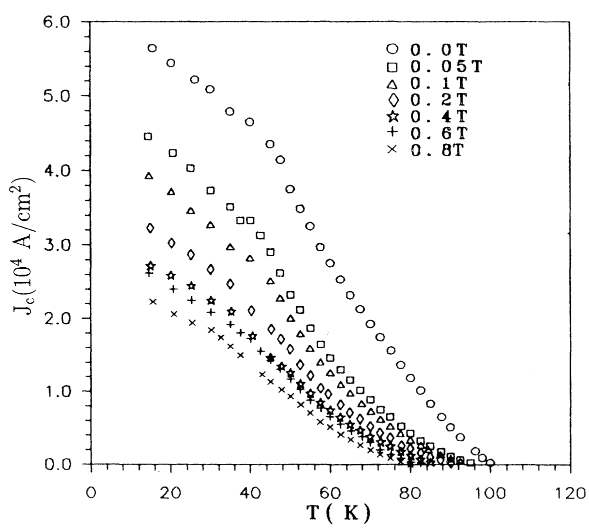

FIG. 1. Dependence of J_c on temperature in applied magnetic fields parallel to the tape surface.

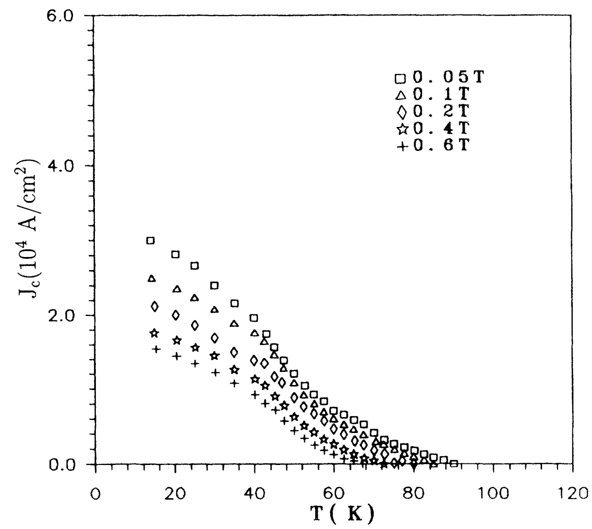

FIG. 2. Dependence of J_c on temperature in applied magnetic fields perpendicular to the tape surface.

from the temperature dependence of the free-energy difference between pinned and unpinned flux quanta, expanded in the form $U(B,t)=U(B,0)(1-bt^2)$. The coefficient $a(B)$ is given by

$$a(B)=kT_c/U(B,0)\ln(dB\Omega/E_c) . \quad (2)$$

Here d is the average hopping distance of the flux bundle, Ω is the attempt frequency of the flux bundle, and E_c is the electric-field criterion that defines J_c. It is evident from Figs. 1 and 2 that the temperature dependence of J_c in the whole temperature range from 10 K to T_{c0} is well fitted by Eq. (1). For $T<40$ K, the coefficient b is equal to zero. That is to say, $U(B,t)=U(b,0)$, which implies that the pinning potential can be regarded as independent of temperature at low temperature below 40 K. We think that the linear decrease of J_c with increasing temperature mainly results from the flux creep at grain boundaries and the flux creep of the component of an applied field along the c-axis direction owing to a little grain misorientation when an applied magnetic field is aligned parallel to the tape surface for $T<40$ K. In this case, a strong intrinsic pinning effect, i.e., a pinning effect by the multilayer structure itself, is theoretically foreseen[11] owing to the modulation of the superconducting parameter along the c axis as ξ_c is much smaller than the stacking periodicity length. The magnetic flux will tend to lie between the $(CuO_2)_2$ blocks, i.e., in the regions where the superconducting order parameter is strongly depressed. We can think that the creep of intragranular flux lying between the $(CuO_2)_2$ layers is negligible at low temperature, below 40 K. On the other hand, for $T>40$ K, the intragranular flux will also experience a creep owing to the decrease of the pinning potential $U(B,t,J)$ with the increase of temperature, and the influence of thermal activation. This will result in a nonlinear reduction of J_c with increase of temperature. For an applied field perpendicular to the tape surface, the linear reduction of J_c mainly comes from the intragranular flux creep owing to a weak extrinsic pinning at low temperature below 40 K, because flux at grain boundaries does not experience the Lorentz force since the current direction between grain boundaries is parallel to the magnetic-field direction according to the brick-wall model.[8] For $T>40$ K, the reduction of J_c becomes rapid showing a nonlinear variation with increase of T. This is likely to originate from a collective effect owing to the decrease of the extrinsic pinning strength and nonlinear variation of the pinning potential barrier on current J for high temperature as discussed below. Comparing Fig. 2 with Fig. 1, we see a strong anisotropy of J_c under magnetic fields. It is associated with different pinning mechanisms along the ab-plane and c-axis directions. Figures 3 and 4 show the dependence of J_c on B when B is perpendicular and parallel to the tape surface, respectively. In the case of B perpendicular to the tape surface, $J_c(B)$ decreases slowly with the increase of B for $T<40$ K. $J_c(B)$ follows a power law: $J_c(B) \propto B^{-\alpha}$ ($\alpha \approx 0.3$) for $T<40$ K. At high temperature over 65 K, $J_c(B)$ follows a exponential law: $J_c(B) \propto \exp(-\beta B)$. This is similar to the results obtained in a Bi(2212) single crystal and oriented film[12] at high temperature. For $40<T<65$ K, as denoted by the arrows in Fig. 3, there is a transition field which drops with increase of temperature. We think that this transition field reflects the transition between the above two different functions for $J_c(B)$. Figure 3 shows that J_c tends to zero for $B=0.4$ T and indicates that the pinning along the c-axis direction is very weak at high temperature. For an applied magnetic field parallel to the tape surface, $T<40$ K, the dependence of J_c on B is similar to that with B perpendicular to the tape surface, as shown in Fig. 4; however, for $T>40$ K, the reduction of J_c with increase of B is much slower than that for B perpendicular to the tape surface. For $40<T<77.6$ K, the transition field is higher than that for B perpendicular to the tape surface, as shown in Fig. 3.

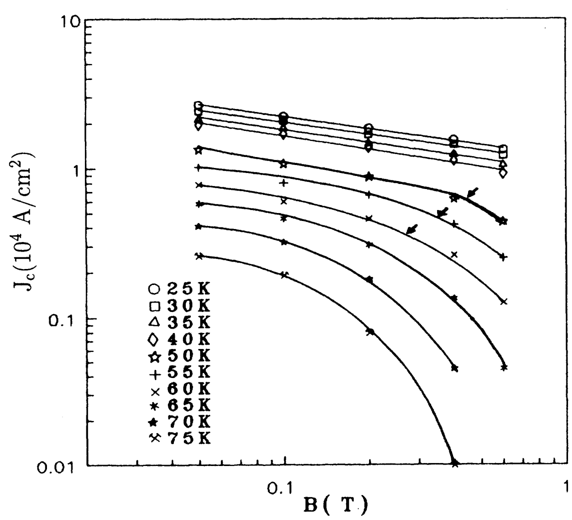

FIG. 3. Dependence of J_c on applied magnetic fields aligned perpendicular to the tape surface at different temperatures.

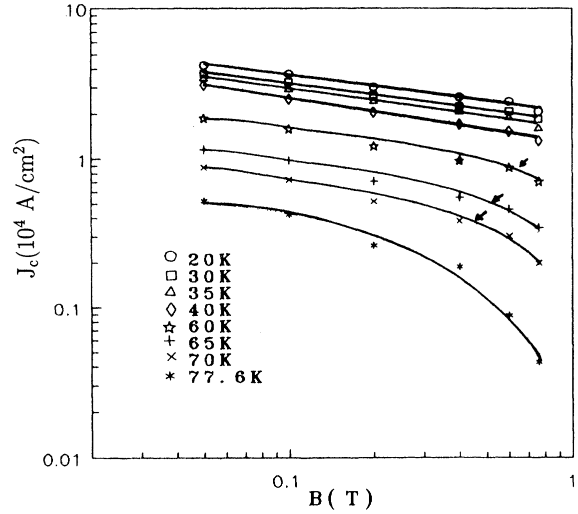

FIG. 4. Dependence of J_c on applied magnetic fields aligned parallel to the tape surface at different temperatures.

The flux-creep model also accounts for the behavior of J_c in an applied field. If an applied magnetic field results in a flux lattice, $J_c(B,t)$ follows the relationship

$$J_c(B,t)=N_p(U(B,0)/1.07(\Phi_0/B)^{0.5}[1-a(B)t-bt^2] \,, \tag{3}$$

as pointed out by Dew-Hughes.[13] Here N_p is the density of the pinning sites and Φ_0 is the flux quantum. If small effects due to the magnetic-field dependence of the logarithmic term in $a(B)$ and $U(B,0)$ are neglected, the critical-current density follows the power-law $J_c \propto B^{-0.5}$ behavior predicted by Eq. (3). Our experimental result of $J_c(B) \propto B^{-0.3}$, which deviates from $B^{-0.5}$, may result from the small effect of $a(B)$ and $U(B,0)$ for $T<40$ K and B both parallel and perpendicular to the tape surface. Therefore, for $T<40$ K, the variation of $J_c(B)$ is controlled by flux creep of a single bundle as pointed out by Anderson and Kim. For $T>65$ K, we assume that the pinning potential follows a law[14]

$$U(B,t,J)=F(t)B^{-\mu}\ln(J_{c0}/J) \,, \tag{4}$$

where $F(t)$ is a function for the dependence of $U(B,t,J)$ on t. The electric field E originating from flux creep follows

$$E=E_0\exp[-U(B,t,J)/T] \,. \tag{5}$$

From Eqs. (4) and (5), we obtain

$$E=E_0(J/J_{c0})^p \,, \tag{6}$$

where $p=F(t)/TB^{\mu}$.

When E reaches the electric-field criterion E_c, the critical-current density $J_c(H,T)$ follows

$$J_c(B,T)=J_c(0,T)\exp[-B^{\mu}T/F(t)\ln(E_0/E_c)] \,. \tag{7}$$

This shows that $J_c(B)$ follows an exponential law,

$J_c(B) \propto \exp(-\beta B^{\mu})$. For our Bi(2223) Ag-sheathed tape sample, $\mu = 1$.

The above discussion shows that the dependence of the pinning potential U(B,t,J) of Bi(2223) Ag-sheathed tapes on current density J follows the relationship $U(J) = U_0 \ln(J_{c0}/J)$ for $T > 65$ K, which is in agreement with the logarithmic barrier model of flux creep. So we think that the intragranular flux experiences a collective effect of the flux creep for high temperature over 65 K. The flux-lattice structure near 40 K may undergo a transition which is similar to the flux-lattice melting near 30 K observed by Gammel *et al.*[15] in a Bi(2212) single crystal. The results of Xu *et al.*[16] that the irreversible field of the Bi(2223) superconductor is very low for $T > 40$ K also seem to support our viewpoint above.

IV. CONCLUSION

For high-J_c textured Bi(2223) Ag-sheathed tapes, the main factor controlling J_c is the flux creep in the temperature range from 10 K to T_{c0} in both applied magnetic-field orientations. However, the creep characteristics at low temperature, below 40 K and high temperature, over 40 K, are different. In other words, for $T < 40$ K, the flux bundles can be considered to be uncorrelated; however, for $T > 40$ K, there exists correlation between flux bundles, i.e., it is necessary to consider the mutual effect between the flux bundles for high temperature. That is to say that the sample experiences the creep of a single flux bundle and a collective effect of the creep of flux bundles at low temperature, below 40 K, and high temperature, over 40 K, respectively. This reveals that the pinning potential $U(B,t,J)$ and flux-lattice structure are different at low temperature, below 40 K, and high temperature, over 40 K. $U(B,t,J)$ follows the relationships $U_0 B^{-\alpha}(1 - J/J_{c0})$ and

$$U(B,t,J) = U_0 \exp(-\beta B)(1 - bt^2)\ln(J_{c0}/J)$$

at low temperature, below 40 K, and high temperature, over 65 K, respectively. The flux lattice seems to undergo a transition analogous to flux-lattice melting in both applied-magnetic-field orientations near 40 K.

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