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Magnetoresistance and *V-I* curves of Ag-sheathed $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10+y}$ tape

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The magnetoresistance and the *V-I* curves $(I>I_c)$ of a well-characterized Ag-clad $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10+y}$ tape (BPSCCO) with $J_c(77\text{ K}, B=0)=10\text{ kA/cm}^2$ have been analyzed in the temperature (T) range 80–110 K and magnetic field (B) up to 60 mT. The results obtained after the correction for the parallel conduction through the Ag sheathing and BPSCCO core are similar to those for corresponding single crystals and the epitaxial thin films. The effective activation energy for the flux creep U_0 is larger than those for the single crystals and thin films of Bi-Sr-Ca-Cu-O (BSCCO) compound. The variations of the differential resistance R_f (deduced from *V-I* curves at $I \gg I_c$) with T and B are consistent with those for the conventional type-II superconductors at elevated temperatures and low fields. Hence the unusual features deduced from the total dissipation in similar tapes are probably due to improper data analysis. The analysis presented here relies on the homogeneity of dissipation within the core which has to be checked for each tape.

I. INTRODUCTION

The investigation of the dissipation in the mixed state is very important for the understanding of the fluxon dynamics and applications of superconductors. Such studies enabled rather detailed understanding of the dissipation in the conventional type-II superconductors employed in the large scale applications.[1] The investigation of high-temperature superconductors (HTS) is more difficult (short samples, low voltage criteria) but again the studies of the magnetoresistance $R(H,T,I<I_c)$ and *V-I* curves $(I>I_c)$ enabled one to single out the effects associated with the granular structure of the polycrystalline HTS (Refs. 2–6) from those inherent to the particular compound.[7,8] Moreover, the results for HTS single crystals and epitaxial films lead to some novel concepts of the flux pinning and motion in HTS compounds.[9,10]

At present, the Ag-clad HTS tapes with Bi-2:2:1:2 and Bi-2:2:2:3 core, are the most promising candidates for the large scale applications of HTS.[11] Most of the knowledge on the flux pinning and motion in these tapes comes from the magnetization measurements whose interpretation is quite complex for such anisotropic granular materials with field dependent I_c. These measurements are also not suitable for the study of dissipation above I_c. Yet a detailed study of dissipation associated with the transport current is complex because silver (Ag) makes about three-quarters of the tape. Accordingly the dissipation in the overwhelming range of the mixed state is dominated with that at Ag. Apparently the nonappreciation of this can seriously affect the conclusions reached from such studies.

Here we present an analysis of $R(H,T)$ and *V-I* curves for a well characterized Ag-clad $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10-y}$ tape (BPSCCO)[12,13] which takes into account the parallel conduction through Ag sheathing and BPSCCO core. The analysis explains the unusual dissipation on the whole tape and reveals the underlying behavior of the core. This behavior at elevated temperatures and rather low fields is very similar to that of corresponding single crystals and epitaxial films. In particular the results show no apparent weak link effects and seem to confirm that fluxon pinning is enhanced in respect to that in films and crystals. The uniformity of the dissipation within the core (vital for the analysis) has been checked for the studied core.

II. EXPERIMENTAL PROCEDURES

The investigated Ag-BPSCCO tape was prepared with the powder-in-tube method. The details concerning this method and the particular tape have been reported elsewhere.[12,13] The core of the tape consisted of almost pure Bi-2:2:2:3 phase, the x-ray-diffraction pattern indicated about 2% of Bi-2:2:1:2 phase. The ratio of the cross section areas of the Ag sheathing and the core was 3.67 and the average thickness of the core 26 μm. The resistance was measured with the standard ac four-probe method at the low frequency $f=18.4$ Hz. The resistance did not depend on the current amplitude within the accessible range $I_0 \leq 10$ mA (corresponding to $J_{tr} \leq 20\text{ A/cm}^2$). The *V-I* curves have been measured with the pulse method[5,13] using the single triangular pulse with the maximum current $I_0 \leq 6$ A. The measurements were performed in the temperature range 80–110 K and in magnetic fields (in the plane of the tape) up to 60 mT. The zero-field critical current density at 77 K was 10 100 A/cm^2.

From the resistance measurements on the intact tape and that with badly damaged core (showing no superconducting transition, only a small decrease of resistance below 108 K) we estimated that the resistance of the core R_c at 300 K is about 400 times larger than that of the whole tape R.[13] As it will be seen later on, this sizable uncertainty in the actual magnitude of R_c has little effect on results of this study. The uniformity of the core has been checked by measuring I_c on short segments (~ 0.3 cm) of the 2-cm long tape. The variation in J_c was within the experimental uncertainty (few percent).

III. RESULTS AND DISCUSSION

Figure 1 shows the resistive transitions of Ag-BPSCCO tape for $I_0 = 1$ mA in the fields $B = 0$, 10, and 30 mT, respectively. The field was applied in the plane of the ribbon, thus probably along the *a-b* crystal plane. The voltage resolution was about 1 nV which corresponded to the eletric field between the voltage contacts $E_c \simeq 1$ nV/cm. The transitions shown in Fig. 1 are neither similar to those observed for the corresponding single crystals or epitaxial films nor to those for ceramic samples. In particular such a strong shift of T_c in such low fields is not observed in single crystals and thin films[14,15] whereas in ceramic samples a characteristic "foot" (associated with the weak links driven into the dissipative state) appears below the main transition in an applied field.[16] Apparently these features (the pronounced S shape of the transition and the shift of T_c) are due to parallel conduction which sets in with the onset of dissipation and leads to the resistance R dominated with that of Ag sheathing R_A as soon as $R_c > R_A$. This is clearly seen from the linear variation of R in the normal state (the magnetoresistance of Ag is negligible for the explored fields and temperatures).

Assuming that the resistivity of the core in the dissipative state ($R \neq 0$) is macroscopically uniform along the tape one can single out the variation of R_c from that of R by assuming the parallel conduction

$$R_c(T,B) = R_A(T,B)R(T,B)/[R_A(T,B) - R(T,B)] .$$

Therefore by using the estimated R_A (which varies linearly with T and is independent of B within the explored temperature and field range) one can deduce $R_c(T,B)$. Figure 1 shows that R_c coincides with R only within few tenths of degree K above $R = 0$. Unlike R, R_c seems to exhibit an exponential increase with temperature

$$R_c \sim R_0 \exp(-U/kT) , \tag{1}$$

which would be expected if the motion of one or more fluxons is thermally activated process with the apparent activation energy U.[17] If U were temperature and field independent R_0 should be equal to R_c in the normal state (R_{cn}).

The $\ln R_c$ vs $100/T$ plots in Fig. 2 show that the exponential variation of R_c extends over several orders of magnitude and starts from the lowest value of R_c (or R, because they are the same in this limit). From the slopes of a linear $\ln R_c$ vs $1/T$ variation one can deduce the effective value of the activation energy which is obviously an extrapolation to $T = 0$ of the line tangent to U at the temperature at which the slope is measured.[17] Assuming that $U(T)$ is linear in T (for $R_c \ll R_{cn}$) the value of U determined in this manner corresponds to $U_0 = U(T = O,H)$. Since U_0 corresponds to the height of the pinning potential the knowledge of U_0 is very important both for the theoretical understanding and practical applications of the tapes. In the inset of Fig. 2 we compare the values of U_0 for our tape with those obtained for an epitaxial Bi-2:2:1:2 film.[18] The recently reported values of U_0 for the epitaxial Bi-2:2:2:3 films[15] agree very well with those for Bi-2:2:1:2 films.[18] However the results for Bi-2:2:2:3 films do not extend to the (low) field range of our measurements. Therefore the values of U_0 for the explored tape appear to be several times larger than those for the best Bi-Sr-Ca-Cu-O (BSCCO) films at

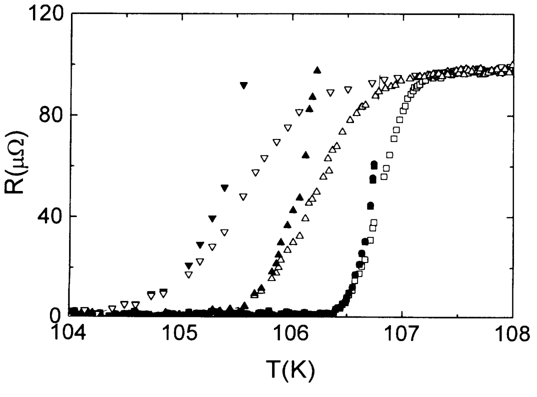

FIG. 1. Resistive transitions of Ag-BPSCCO tape (empty symbols) and its BPSCCO core (full) in magnetic fields $B = 0$, 10, and 30 mT (right to left).

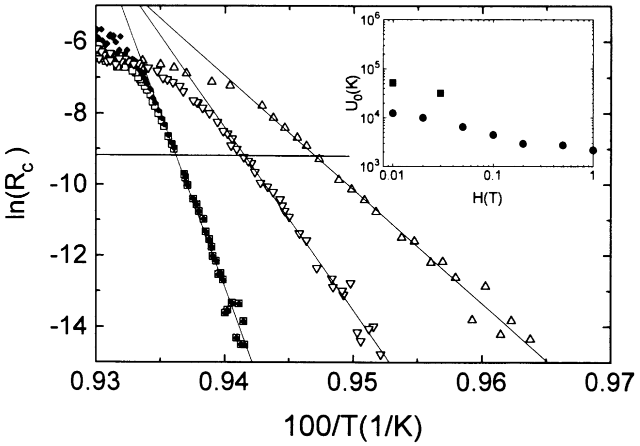

FIG. 2. Arrhenius plot of the resistive transitions of BPSCCO core R_c in magnetic fields $B = 0$, 10, and 30 mT (left to right). Full symbols denote variation obtained for twice smaller ratio R_A/R (R_A and R are the resistance of Ag sheathing and the tape, respectively). Inset shows the activation energy U_0 against B: (■) present results, (●) results for epitaxial Bi-2:2:1:2 film (Ref. 18).

the same fields. This seems to be consistent with the enhancement of the fluxon pinning in Ag-BPSCCO tapes in respect to that in the single crystals.[19] We note however that part of the difference between the U_0 values for our tape and those of the epitaxial films[15,18] may be due to different field geometry ($B \| c$ in films whereas $B \perp c$ in the tape). Indeed, like in parent compounds, the pinning in tapes is strongly anisotropic[11] and this should show up in the values of U_0 for the two directions of B. Such an anisotropy in U_0 has indeed been observed in an early investigation of U_0 in the c-axis oriented $(\mathrm{Bi,Pb})_2\mathrm{Sr}_2\mathrm{Ca}_2\mathrm{Cu}_3\mathrm{O}_{10+y}$ thin films.[14] However, in this case the values of U_0 obtained for $B \perp c$ were sizably lower than those for $B \| c$ in the epitaxial BSCCO films.[15,18] (This illustrates the importance of U_0 in monitoring the progress made in the preparation of HTS exhibiting the enhanced flux pinning.)

The results depicted in Fig. 2 and the inset can also yield the field dependence of U_0. Our measurements seem to indicate $U_0 \sim B^{-0.5}$ which is consistent with the results for the epitaxial BSCCO films.[15,18] We note that J_c of the studied[13,20] and the other similar tapes shows the same field dependence, which has been predicted for J_c of polycrystalline HTS at lower fields.[9] This emphasizes the correlation between U_0 and the fluxon pinning in Ag-BPSCCO tapes. However, in contrast to J_c which is linked with the worst property (or part) of a given tape, U_0 (which is determined from the variation of R_c extending over several orders of magnitude) is more likely to represent the bulk properties of the core.

As expected at elevated R_c, $\ln R_c$ vs $1/T$ deviates from the straight line. Since for our tape these deviations occur around $R_c(T,B) \approx R_f(T,B)$ (R_f is the differential resistance, i.e., the slope of the V-I curve at elevated currents where V varies linearly with I) we believe that they indicate the onset of the flux-flow as in conventional type-II superconductors.[21] (The method for the extraction of R_f form the V-I curves of the investigated tape and the variations of R_f with T and B will be given later on.)

It is important to consider the influence of the uncertainty in the estimated value of R_A (hence also R_c) on the above results. Full symbols in Fig. 2 denote the variation of R_c obtained for the deliberately taken two times smaller ratio R_A/R. Obviously the absolute value of R_c has increased for about the same amount but neither the slope (U_0) of $\ln R_c$ vs $1/T$ nor the condition $R_c \simeq R_f$ for the deviation from the exponential variation of R_c did change. This indicates that the parameters such as U_0 and R_f/R_{cn} are rather insensitive to the uncertainty of R_A and therefore lends a strong support to the above analysis.

The parallel conduction (which sets in simultaneously with the onset of dissipation) should also be taken into account when analyzing the V-I curves of the tapes.[13,22] If we denote the total current with I_T and that through the core with I one has

$$\frac{I}{I_T} = \frac{R_A}{R_A + R_C} . \tag{2}$$

Equation (2) shows that the measured V-I_T characteristic represents that of the core (V-I) only for $R_C \ll R_A$, i.e., for $I_T \cong I_C$. Therefore within the limits of the field criterion employed I_c of the tape is that of the core but as soon as the finite voltage develops across the sample the actual V-I characteristic deviates strongly from the measured V-I_T curve. This is illustrated in Figs. 3 and 4 for the case of the fixed field $B=0$ and fixed temperature $T=80.5$ K, respectively. Obviously the identification of V-I_T curves with V-I ones would lead to the conclusion that the behavior of BPSCCO core is basically different both from those of the ceramic HTS (Refs. 3–6) and the conventional type-II superconductors.[21] In particular, an unusual flattening of the V-I_T curves at low temperatures associated with different temperature variations of the observed dynamic resistance (dV/dI_T) at low (1μV) and higher voltages (50μV), respectively, has been reported.[22] Whereas dV/dI_T at low voltages showed a little variation with T for $T \leq 90$ K that at elevated voltages showed approximately linear increase for $60\ \mathrm{K} \leq T \leq 90$ K. Such behavior is expected from Eq. (2) since at elevated voltages $R_C \gg R_A$ and therefore dV/dI_T simply reflects a linear variation of R_A with T for $60\ \mathrm{K} \leq T \leq 90$ K. (This variation does not appear at low voltages because $R_C \ll R_A$ and hence $I_T = I \cong I_c$.) Indeed, as shown in the inset in Fig. 3 when dV/dI is calculated from dV/dI_T for our tape at elevated voltage ($I \gg I_c$) it shows a little variation with T except for $T > 96$ K [i.e., close to the phase boundary T_c (Refs. 21 and 23)]. Therefore both the magnitude and temperature variation of $R_f = (dV/dI)_{I \gg I_c}$ for our[13] and probably other similar tapes[22] are consistent with the low-field (self-field) flux-flow resistance of the conventional type-II superconductors.[21]

Similarly V-I_T curves measured at a fixed temperature and applied field B should be corrected in order to gain the true V-I characteristic of the core (Fig. 4). Since at low fields and high temperatures the magnetoresistance of silver is negligible one can use $R_A(T,B=0)$ when per-

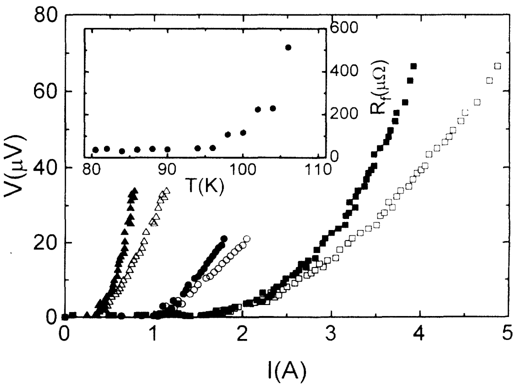

FIG. 3. V-I curves for Ag-BPSCCO tape (empty symbols) and its BPSCCO core (full) at $T=80.5$, 90.1, and 100.1 K (right to left). Inset: temperature variation of differential resistance R_f of the BPSCCO core (deduced from the slope of a linear V-I dependence at elevated I).

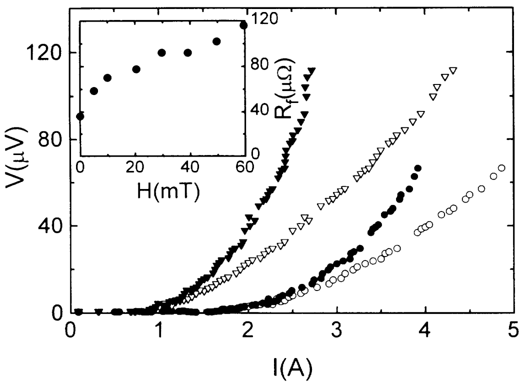

FIG. 4. *V-I* curves for Ag-BPSCCO tape (empty symbols) and its BPSCCO core (full) at 80.5 K and $B = 0$ and 60 mT. Inset: field variation of differential resistance R_f of BPSCCO core (deduced from the slope of linear *V-I* dependence at elevated *I*).

forming this correction. (For high fields and/or low temperatures one has to measure the magnetoresistance of Ag sheathing.) The variation of R_f with B for our tape (core) deduced from the true *V-I* curves is shown in the inset in Fig. 4. This variation[24] is quite consistent with that observed in the conventional type-II superconductors at low fields and high temperatures.[23]

In view of the above discussion the V-I_T curves of Ag-clad BPSCCO tapes can only be used in order to determine I_c (and of course its variation with B and T). For any other purpose the results have to be corrected in order to gain the true *V-I* characteristic. For our and probably other well prepared tapes the true variations of R_f with T and B are consistent with those observed in conventional type-II superconductors and therefore like $R_c(T,H)$ do not show the effects of weak links within the explored T and B range. A more detailed analysis of the whole *V-I* curves and its comparison with that for $R_c(H,T)$ is hampered at present with rather low field criterion inherent to the pulsed measurements of V-I_T curves of short samples with high J_c values.

Finally we note that *V-I* curves can be used in order to deduce the macroscopic uniformity of the resistivity of the core in the dissipative (mixed) state. (This uniformity is the prerequisite for the applicability of the simple parallel current corrections performed above.) If the resistivity is uniform the intercept of the linear *V-I* variation at elevated $I(I \gg I_c)$ extrapolated to I axis I_c' should be the same as the average critical current $\langle I_c \rangle$ deduced from the critical current distribution function CCD.[25,26] For the investigated tape indeed $\langle I_c \rangle = I_c'$ was observed. As mentioned in Sec. II the macroscopic uniformity of the core can be deduced from the variation of I_c along the length of the tape. For the present and other similar tapes the variations of I_c are, in general, within the experimental uncertainty in I_c determined by the pulse method (few percent) and any larger variation (5–10 %) if present can be easily associated with the local change in the shape (width) of the tape. This contrasts sharply with the ceramic samples for which the variations in I_c for a factor of several are usually observed.[27] Therefore the applicability of a simple correction for the parallel conduction in present day Ag-BPSCCO tapes seems justified. This correction can be performed with a quite high precision providing that the resistivity of the Ag tape which has undergone the same treatment as the entire tape is separately measured.

IV. CONCLUSION

An analysis of the superconducting transitions and *V-I* curves of a well characterized Ag sheathed $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10-y}$ tape in terms of parallel conduction through the Ag sheathing and BPSCCO core has been performed. This analysis (performed to our knowledge for the first time for an Ag sheathed HTS tape) reveals the underlying dissipation within the core which is very different from that on the whole tape and is quite similar to that observed in *c*-axis oriented thin films of the same compound.[14,15] The novel features are that the effective activation energy for fluxon motion U_0 is larger than that in the corresponding thin films and single crystals (which is consistent with the magnetically determined variations of the irreversibility lines in these substances[19]) and that the dissipative behavior at the transport currents well beyond I_c (the flux-flow regime) can be investigated. As deduced from the variations of the differential (slope) resistance R_f with temperature and magnetic field the behavior of the core in the flux-flow regime is consistent with that of the conventional type-II superconductor in the same range of the reduced temperature (T/T_c) and low magnetic field.[21,23]

In general the analysis presented in this paper enables a detailed investigation of the flux pinning and motion in Ag-HTS tapes (both mono- and multifilamentary ones) by means of the transport measurements. The analysis of the transport measurements for HTS tapes is more straightforward than that of the magnetic measurements and is also more directly related to their technological applications. Particularly important is the possibility to deduce the parameter U_0 which is expected to characterize rather better the progress made in the production of the advanced tapes than J_c (which is determined by the worst properties of a given tape). Simultaneously the detailed investigation of the variations of U_0 over a broad range of B, T, and J (which is possible for tapes) may help to elucidate some still unclear points regarding the flux pinning and motion in HTS compounds.

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