Modeling the current-voltage characteristics of silver-sheathed Bi-Sr-Ca-Cu-O tapes

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Measurements of voltage-current (V-I) characteristics and critical currents of 2212 and 2223 Ag-clad Bi-Sr-Ca-Cu-O tapes at $0<B<7$ T and 4.2 and 77 K are presented. We show that the V-I curves are nonlinear at $I<I_c$ and become linear above the critical current $I>I_c$ due to the effect of the Ag cladding. It is shown that the V-I curves can be well described by a simple universal formula, which enables one to extract $I_c(T, B)$ and the flux creep rate $s(T, B)$ from the resistive measurements, taking into account the effects of voltage criterion, strong nonlinearity of $V(I)$ and $I<I_c$ and the dependence of the resistivity of Ag upon T and B. For a 2212 tape, $I_c(B)$ is shown to decrease as $B^{-\alpha}$ with $\alpha=0.15$ at 4.2 K, and exponentially at 77 K. For a 2223 tape, $I_c(B)$ displays a power law dependence with $\alpha=0.1$–0.3 at 4.2 K, whereas at 77 K $I_c(B)$ can be well described by the formula $I_0 b^{-1/2}(1-b)$, where $b=B/B^*$, and B^* is the irreversibility field. The results are interpreted in terms of strong bulk pinning modified by thermal fluctuations.

Recent reports of high critical-current densities, J_c, in Bi-Sr-Ca-Cu-O/Ag (BSCCO) tapes[1–3] have focused more attention on large-scale applications of high T_c superconductors. At the same time, the mechanisms which determine J_c in BSCCO tapes remain unclear due to their complicated multiphase microstructure[4,5] and to the specific features of flux dynamics and pinning which result from short coherence length, high anisotropy, and significant thermal fluctuations.[6] This leads to giant flux creep and a strong dependence of J_c upon the voltage criterion, V_c, in resistive measurements or on the sweep rate in magnetization measurements,[7,8] which manifests itself in a vanishing of $J_c(T,B)$ at the irreversibility field $B^*(T)$ well below the upper critical field $B_{c2}(T)$. At $B<B^*(T)$ the critical current can exhibit qualitatively different behavior in various regions of temperature T and magnetic induction B. For instance, $J_c(B)$ of BSCCO tapes at 4.2 K sharply drops at low B and then displays a plateau up to $B\sim 20$ T, whereas at higher T the $J_c(B)$ dependence becomes exponential.[1–3] These quite different characteristics appear to indicate that there is no universal mechanism of critical current control, although some factors which determine $J_c(T,B)$ may dominate in certain regions of T and B. For example, $J_c(B)$ reveals a Josephson-like behavior at low B and T, which may result from a weak-link structure along the c-axis,[9] whereas the exponential decrease of $J_c(T,B)$ at larger T and B may correspond to a smearing of the bulk pinning potential by thermal fluctuations.[10] Under these circumstances, any particular operational definition of J_c cannot be expected to be equally valid in all domains of T and B.

These features of $J_c(T,B,V_c)$ can be extracted from the voltage-current (V-I) characteristics which, together with the Maxwell equations, determine the current-carrying capacity and relaxation of the critical state. In this letter we present measurements of the V-I characteristics of $Bi_2Sr_2Ca_2Cu_3O_x$(2223) and $Bi_2Sr_2CaCu_2O_x$ (2212) Ag-clad tapes at 4.2 and 77 K for $0<B<7$ T. A universal scheme is proposed to describe $V(I)$ of the BSCCO tapes and to study the dependencies of J_c and flux creep parameters upon T, B, V_c, and the properties of the normal cladding. Different regimes of critical-current control are shown to exist, depending on T and B.

The tapes were prepared by the oxide-powder-in-tube method as described previously,[4,5] then rolled, sintered, and cut into 2 cm long pieces. The samples had a BSCCO core $\simeq$25–50 μm thick and $\simeq$2 mm wide, surrounded by Ag sheath of thickness $\simeq$25–40 μm. The field B was perpendicular to the plane of the tapes and was thus approximately parallel to the c-axis. The I-V curves of the 2212 and 2223 tapes measured by the standard four-probe method at various T and B are shown in Figs. 1 and 2.

Our analysis of the experimental data exploits the large difference between the resistivity of the Ag cladding, ρ_{Ag}, and the flux flow resistivity, $\rho_f=\rho_n B/B_{c2}$, where ρ_n is the normal state resistivity of BSCCO ($\rho_n=10^3$–$10^4\rho_{Ag}$). In this case, all current in excess of I_c is shunted into the Ag sheath, and the superconducting core remains in the flux creep regime, even for I considerably exceeding I_c. The absence of flux flow in BSCCO allows one to write the electric field $E(J)$ at $J<J_c$ in a fairly general form $E(J)=E_c\exp[-U(J)/kT]$. Here $U(J)$ is the flux creep barrier which is a nonlinear function of J and vanishes at $J=J_c$, E_c is a crossover electric field between the flux flow and flux creep regimes, and J is the current density in the superconductor. At small J the function $U(J)$ can be qualitatively different in various models of flux dynamics,[6] however, in resistive measurements limited by a particular voltage sensitivity (usually $\sim$0.1 μV), the details of $U(J)$ at $J\ll J_c$ are irrelevant, and the observed $V(I)$ at $B<B^*(T)$ is determined by the dependence of $U(J)$ near $J=J_c$. Then $E(J)$ can be obtained by expanding $U(J)$ in a power series in J_c-J, keeping only the first term, i.e., $U(J)/kT=(J_c-J)/J_1$.[11] This yields

$$E(J)=E_c\exp[(J-J_c)/J_1] \qquad (1)$$

where $J_1=kTJ_c/U_0$ can be expressed via the observed flux

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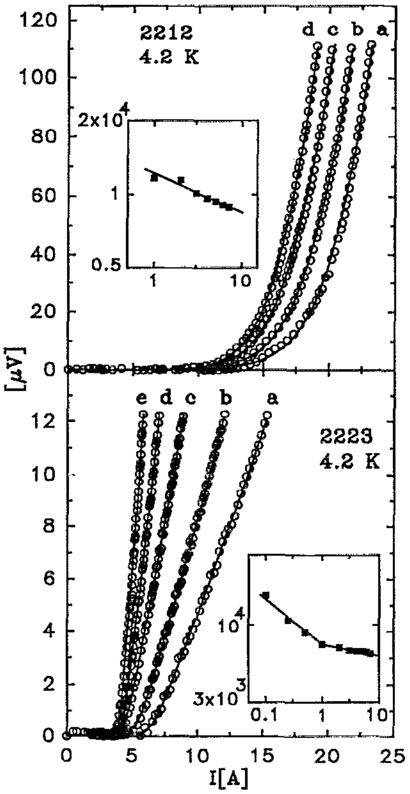

FIG. 1. V-I curves at 4.2 K and different B, the solid curves corresponding to Eq. (2). The upper figures shows $V(I)$ for the 2212 tapes at: (a) 2 T, (b) 3 T, (c) 5 T, and (d) 6 T. The lower figure concerns the 2223 tapes at: (a) 0.25 T, (b) 0.5 T, (c) 1 T, (d) 2 T, and (e) 4 T. Insets show J_c [A/cm^2] vs $B[T]$, the solid lines corresponding to $B^{-\alpha}$, with $\alpha=0.15$ (2212 tapes), or $\alpha=1/3$ at $B<1$ T and $\alpha=0.07$ at $B>1$ T (2223 tapes).

creep rate, and U_0 is an apparent flux creep activation energy. Using Eq. (1), we can write the total current flowing through the tape, I, as the sum of currents through the superconductor and the normal sheath:

$$I=I_c+I_1 \ln(V/V_c)+V/R \qquad (2)$$

where $I_c=J_cA$, $I_1=J_1A$, A is the cross-section of the superconductor, and R is the total resistance of the normal cladding. Therefore, the only assumption behind Eq. (2) is that the flux dynamics at $J<J_c$ has a thermally activated character, regardless of the particular microscopic mechanisms. In other words, flux creep is assumed to be the main source of nonlinearity of $V(I)$ at small V in BSCCO, unlike the low T_c composites, where the nonlinearity of $V(I)$ often results from macroscopic variations of I_c along the superconducting filaments.[12]

As follows from Eq. (2), the transition from the highly nonlinear to the quasilinear region of $V(I)$ occurs at $V\sim V_1=RI_1$ when the differential resistance of the superconductor, $dV/dI=V/I_1$, becomes larger than R, and all excess current above I_c flows through the normal cladding. Notice that in the presence of flux creep there is no unique definition of I_c. Indeed, one can arbitrarily change both parameters I_c and V_c in Eq. (2) provided that the observed

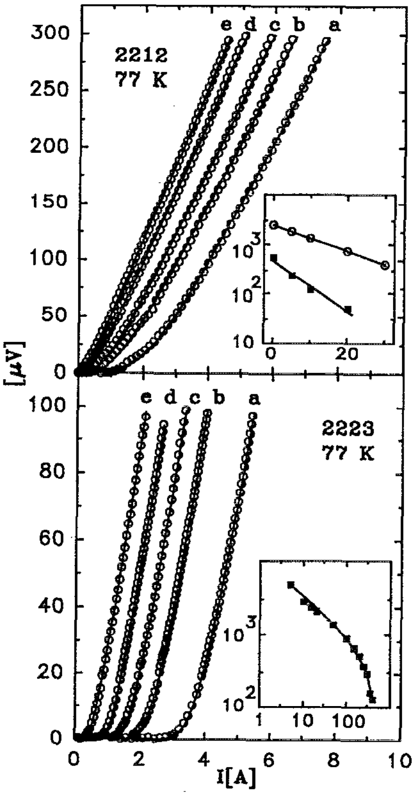

FIG. 2. V-I curves at 77 K and different B, the solid curves corresponding to Eq. (2). The upper figure concerns the 2212 tapes at: (a) 0 T, (b) 5 mT, (c) 10 mT, (d) 20 mT, and (e) 30 mT. Inset shows J_c [A/cm^2] versus B [mT] for different E_c: 1 μV/cm (open circles), and the extrapolation of the linear part of $I(V)$ down to the intersection with the I-axis (black squares). The lower figure concerns the 2223 tapes at: (a) 5 mT, (b) 10 mT, (c) 20 mT, (d) 50 mT, and (e) 200 mT. Inset shows J_c[A/cm^2] as a function of B [mT], where the solid curve corresponds to $J_0b^{-1/2}(1-b)$ with $b=B/B^*$.

quantity $I_c-I_1 \ln V_c$ remains constant. Hence, any pair of critical currents I_{c1} and I_{c2} at different voltage criteria V_{c1} and V_{c2} are linked as follows

$$I_{c2}=I_{c1}+I_1 \ln(V_{c2}/V_{c1}) \qquad (3)$$

where I_1 can be directly extracted from the slope of ln V versus I.

Figures 1 and 2 show that Eq. (2) describes the experimental data very well for both 2212 and 2223 tapes. Here I_c, I_1, and R were treated as fit parameters with I_c defined at $E_c=1$ μV/cm. To provide a supplementary check of the model, we measured $\rho_{\mathrm{Ag}}(4.2\ \mathrm{K},B)$ for the Ag used for sheathing of our tapes and then compared it to ρ_{Ag} extracted from the fit. We found that both resistivities $\rho_{\mathrm{Ag}}(T,B)$ exhibit similar strong dependencies on B, although the derived ρ_{Ag} proved to be 10%–30% larger than the experimental values described by $\rho_{\mathrm{Ag}}(4.2\ \mathrm{K},B)$ [$\mu\Omega$ cm]$=0.03+0.8B[T]$. This may be due to contamination of Ag during the process used for optimization of J_c and uncertainties in Ag cross-sectional area when estimating ρ_{Ag} from the fit. Since the V-I curves of both the 2212 and 2223 tapes could be well described by Eq. (2), we proceeded to extract the $I_c(T,B)$ and $I_1(T,B)$ dependencies from resistive measurements done at different T and

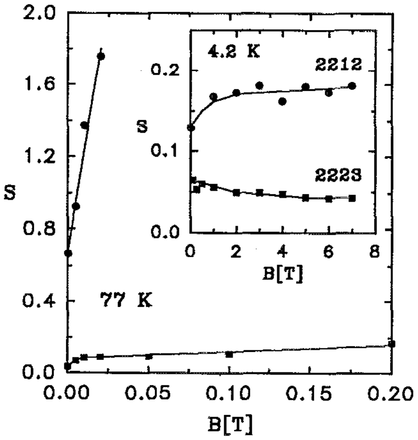

FIG. 3. The flux creep rate $s(B)$ at 77 K for the 2212 (circles) and 2223 (squares) tapes, respectively. Inset shows $s(B)$ at 4.2 K.

B. Such an analysis reveals various regimes of flux dynamics and pinning in different regions of T and B.

$J_c(B)$ is shown in the insets to Figs. 1 and 2. As follows from Fig. 1, for the 2212 tape at 4.2 K, $J_c(B)$ decreases as $B^{-0.15}$. On the other hand, at 77 K, the $J_c(B)$ dependence becomes exponential, both the magnitude and field dependence of $J_c(B)$ being very sensitive to the voltage criterion V_c (Fig. 2).

For the 2223 tape at 4.2 K the $J_c(B)$ exhibits a kink at $B=1$ T, such that $J_c \propto B^{-\alpha}$ with $\alpha=0.33$ at $B<1$ T and $\alpha=0.07$ at $B>1$ T. The smaller value of α at $B>1$ T indicates a weak field dependence of J_c at 4.2 K, correlating with the plateau in ln $J_c(B)$ reported by other groups.[1-3] However, our experimental data better correspond to a power law dependence ($J_c \propto B^{-\alpha}$), which, if plotted as ln J_c versus B, also displays an apparent plateau provided that the field range examined ($0<B<B_{\max}$) is much smaller than B^*. This effect is especially pronounced at low temperatures, due to high values of $B^* \sim B_{c2} \sim 100$–200 T in BSCCO, much larger than our $B_{\max}$ of 7 T. By contrast, at 77 K, the irreversibility field B^* drops below 1 T, due to the giant flux creep in BSCCO. In this case the extracted $J_c(B)$ can be well described by the dependence $J_c(b)=J_0(1-b)/b^{1/2}$, which is similar to that observed for strong core pinning,[13] where the reduced field $b=B/B^*$ is normalized to $B^*=0.52$ T instead of B_{c2} (Fig. 2).

Figure 3 shows the dimensionless flux creep rate $s(B)=I_1/I_c$ for both tapes at 4.2 and 77 K. At $B<B^*$, $s(B)$ ranges from 0.03 to 0.2, in accordance with flux creep measurements.[3] The exception is the 2212 tape at 77 K for which $s(B)$ becomes ~ 1 because of small values of $B^* \simeq 0.01$ T. For the 2212 tape, the function $s(B)$ increases with field at high B at both 4.2 and 77 K. The increase is approximately linear, which corresponds to the dependence $U_0 \propto 1/B$ given by a model of strong single-vortex pinning.[14] For the 2223 tape at 77 K, $s(B)$ also grows linearly with B, whereas at 4.2 K, $s(B)$ displays an anomalous decrease with B.

We suppose that the above features of $J_c(B)$ and $s(B)$ at $B<B^*$ indicate a conventional bulk pinning mechanism rather than weak link behavior. As follows from our analysis, $J_c(B)$ can be described by the formula $J_0 b^{-\alpha}(1-b)^{\beta}$ with $b=B/B^*$, where the replacement of B_{c2} by B^* accounts phenomenologically for the strong flux creep in BSCCO. The kink in $J_c(B)$ at 1 T and 4.2 K for the 2223 tape may correspond to a crossover between different mechanisms of critical current control, perhaps, intergrain Josephson coupling and intragrain bulk pinning. In the 2212 tape at 77 K, the field B^* drops well below B_{c2}, leading to the exponential decrease of $J_c(B)$ even at small B (Fig. 2). Such a behavior of $J_c(B)$ may be due to strong thermal fluctuations of the vortex positions,[10] although the definition of J_c at these T and B becomes uncertain due to the large values of $s(T,B)$ and the significant dependence of J_c on V_c. Nevertheless, Eq. (2) gives a surprisingly good description of the observed V-I curves in this case as well.

In conclusion, we have shown that the V-I curves of the 2212 and 2223 tapes can be well described by a universal model over a wide region of V, T, B space. The method proposed has enabled us to extract $J_c(T,B,V_c)$ and $I_1(T,B)$ unambiguously from resistive measurements. The dependencies $J_c(B)$ and $I_1(B)$ obtained indicate various regimes of critical-current control in different regions of T and B.

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