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Flux-Flow Resistivity of Three High-Temperature Superconductors*

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***Abstract*—Results of experiments on flux-flow resistivity (the relationship of voltage to current) of three high-temperature superconductors are described. The superconductors are a melt-cast BSCCO 2212 rod, a single-filament BSCCO powder-in-tube (PIT) tape, and a multifilament PIT tape. The flux-flow resistivity of these superconductors was measured at three temperatures: 77 K (saturated liquid nitrogen), 87 K (saturated liquid argon), and 67 K (subcooled liquid nitrogen). Implications of the present results for practical applications are discussed.**

I. Introduction

The 1 μV/cm electric field criterion is usually used to determine the critical current density of a superconductor in the laboratory. This criterion is convenient but may not be useful in practical applications for high-temperature superconductors (HTSs). It is well known that, when the current is varied, there is a transition (dissipative) state between the superconducting and the normal states of a superconductor. For low-temperature superconductors, this transition occurs over a rather narrow current range (as a fraction of the critical current). For some HTSs, this transition occurs over a relatively wide range of currents (one order of magnitude larger than the critical current is possible) [1],[2]. Thus, the 1 μV/cm criterion for HTS applications may be overly conservative. An alternative, which is more relevant for engineering applications, is to employ flux-flow resistivity, the relationship of voltage V to current I (which is related to dissipation and generation of heat) as the criterion for determining the maximum current density allowed for a given application. Another reason for measuring the flux-flow resistivity of HTSs is that the transient temperature distribution depends strongly on the resistivity of the HTS in the transition regime [3],[4].

In this paper, we describe the results we obtained when we measured the flux-flow resistivity of a melt-cast BSCCO 2212 rod, a single-filament BSCCO-2223 powder-in-tube (PIT) tape, and a multifilament BSCCO-2223 PIT. The flux-flow resistivity of these superconductors were measured at 77 K (saturated liquid nitrogen), 87 K (saturated liquid argon), and 67 K (subcooled liquid nitrogen).

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II. Experimental Apparatus and Procedures

The standard four-point measurement technique was employed for all tests. Braided current leads were soldered to the ends of the sample and connected to a DC power supply. The tests at 77 K were conducted in an open dewar with liquid nitrogen, and the tests at 87 K were conducted in the same open dewar with liquid argon. Tests at 67 K were conducted in a dewar with subcooled liquid nitrogen at 1 atm pressure. The method of producing subcooled liquid nitrogen is similar to that described by Richardson, Scurlock, and Tavner [5] and is shown schematically in Fig. 1. A copper coil is submerged in a pool of liquid nitrogen. One end of the coil is connected to a cryogenic needle valve and the other end of the coil is connected to a vacuum pump. By opening the needle valve, liquid nitrogen flashes inside the coil, the surrounding liquid is cooled and thus the temperature of the liquid nitrogen is reduced. All tests were conducted under steady-state conditions. Table I lists the dimensions of various superconductor samples and the distance between the voltage taps.

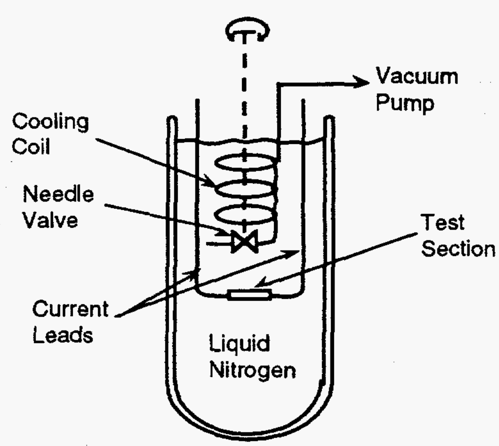

Fig. 1. Schematic diagram of experimental setup for producing subcooled liquid nitrogen at 67 K.

TABLE I
APPROXIMATE DIMENSIONS OF THE SAMPLE SUPERCONDUCTORS

Sample	Dimensions (mm) Width	Thick-ness	Super-conductor Fraction	Distance between Voltage Taps (mm)
Single-filament BSCCO-2223 PIT tape	4.16	0.23	0.27	10
Multifilament BSCCO-2223 PIT tape	4.32	0.25	0.25	15
Melt-cast BSCCO-2212 rod	diameter = 7.85		-	87

III. Experimental Results

A. Single-Filament BSCCO-2223 PIT Tape

Fig. 2 shows the flux-flow resistivity in terms of V vs. I of the single-filament BSCCO PIT tape at three temperatures. The critical currents (1 μV/cm criterion) are $\approx I_c = 7$, 15, and 20 A at T = 67, 77, and 87 K, respectively. Beyond the critical current, there is a linear region on the V-vs.-I curve when T = 77 and 87 K. The data for T = 67 K exhibited a rather unusual behavior in that the voltage drop tends to approach that for T = 77 K at large current. During the experiments at T = 67 K, we observed that the temperature (measured by a silicon diode located adjacent to the tape) fluctuates and is difficult to control within ±1.0 K. Fig. 3 shows the measured temperature as a function of current during the experiments. The cryogenic valve that we used in the experiment was not adequate for fine control of liquid flow; this problem resulted in the temperature variation shown in Fig. 3. Another problem with the experimental setup shown in Fig. 1 is that a long time was required for the system to reach a new steady state after adjustment of the needle valve. Furthermore, it is not clear that the entire sample is at a uniform temperature because there may be some convection current in the liquid nitrogen even under steady-state conditions. For these reasons, the data at T = 67 K in Fig. 2 can be viewed only in a qualitative way to indicate the trend.

B. Multifilament BSCCO-2223 PIT Tape

Fig. 4 shows a plot of V vs. I at three temperatures for a multifilament BSCCO PIT tape. The results are similar to those shown in Fig. 2 for the single-filament tape. The critical currents (1 μV/cm criterion) are $\approx I_c = 23$, 35, and 55 A at T = 87, 77, and 67 K, respectively. Again, the data for T = 67 K tend to approach that for T = 77 K at large current, a phenomenon that is probably due to the uncertainty in temperature described previously.

As shown in Table I, the dimensions and superconductor fraction of the single-filament and the multifilament tapes are approximately the same. Comparison of the critical current

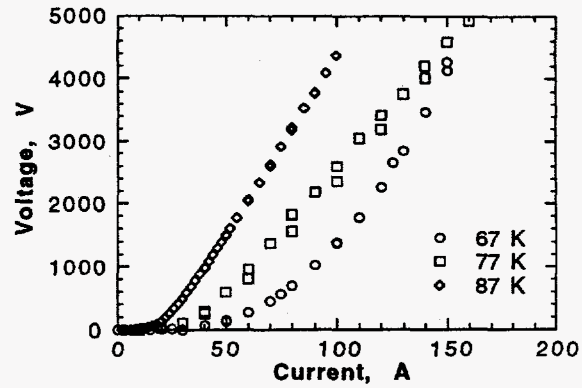

Fig. 2. Voltage vs. current for single-filament BSCCO-2223 PIT tape at 67, 77, and 87 K.

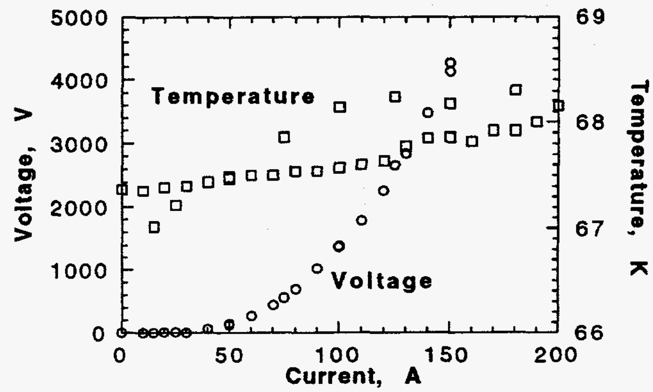

Fig. 3. Variation of voltage and temperature with current for single-filament BSCCO-2223 PIT tape.

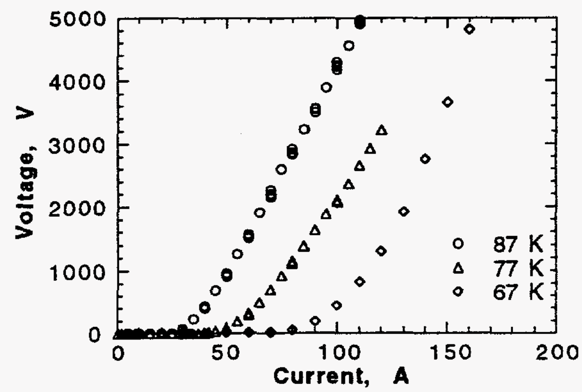

Fig. 4. Voltage vs. current for multifilament BSCCO-2223 PIT tape at 67, 77, and 87 K.

of the two tapes indicates that the multifilament tape exhibits better electrical properties than the single-filament tape. For example, the critical current of the multifilament tape is 35 A at 77 K, whereas that of the single-filament tape is only 15 A at 77 K. This is probably because the multifilament tape contains more interfacial area, which tends to promote formation of the BSCCO-2223 phase [6].

For silver-sheathed composite superconductors such as the BSCCO-2223 PIT tapes, the conductor is in a current-sharing regime as soon as the transport current exceeds the critical current of the tape. The current in the silver (I_{Ag}) and that in the BSCCO-2223 (I_B) can be calculated from the measured voltage drop and current. Assuming there is no voltage drop in the transverse direction, the current in the silver is

$$I_{Ag} = V/R_{Ag} \quad (1)$$

where the resistance of the silver R_{Ag} is

$$R_{Ag} = \rho_{Ag} * \ell/A_{Ag} \quad (2)$$

and ρ_{Ag} is the resistivity of the silver, ℓ is the distance between the voltage taps, and A_{Ag} is the cross-sectional area of the silver. The current in the BSCCO-2223 is

$$I_B = I - I_{Ag} \quad (3)$$

where I is the total transport current. The resistivity of silver at 77 and 87 K is 0.28×10^{-6} and 0.34×10^{-6} Ω-cm, respectively. The cross-sectional area of the silver can be calculated from the dimensions of the tape and the superconductor fraction given in Table I. The distance between the voltage taps is also given in Table I.

The calculated I_{Ag} and I_B for the single- and multifilament BSCCO-2223 PIT tapes at 77 K are shown in Figs. 5 and 6, respectively. Two distinct regions are observed as the transport current is increased. Initially, the current in the BSCCO superconductor increases linearly, while the total transport current and the current in the silver remains zero in this region. When the total transport current is increased beyond a certain value, which we shall call I_m, the current in the BSCCO superconductor can no longer increase and either levels off at a constant value or drops slightly at still higher total current. Meanwhile, the current in the silver begins to increase linearly while the current in the superconductor is leveling off. This means that initially, while the total current is less than I_m, all current is in the superconductor. When the total current exceeds I_m, the current in the superconductor remains nearly constant and all excess current goes to the silver. Similar results were reported by Kunchur et al. [7].

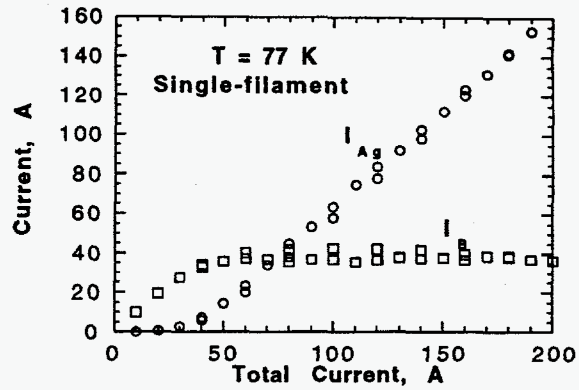

Fig. 5. Calculated current in BSCCO superconductor (I_B) and the silver (I_{Ag}) as a function of total current for single-filament BSCCO-2223 PIT tape at 77 K.

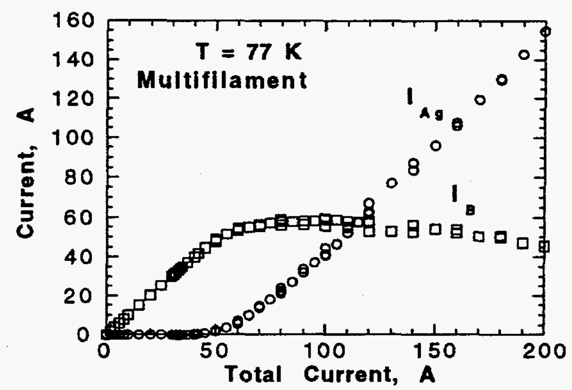

Fig. 6. Calculated current in BSCCO superconductor (I_B) and the silver (I_{Ag}) as a function of total current for multifilament BSCCO-2223 PIT tape at 77 K.

The fact that below I_m, all current is in the BSCCO superconductor suggests that, for practical applications, I_m should be considered an alternative for the maximum allowable operating current instead of I_c (defined by the 1 μV/cm criterion).

For comparison, let us define I_m quantitatively as the total current when I_{Ag} = 1.0 A. Table II shows the I_m and I_c for the single- and multifilament BSCCO tapes at 77 and 87 K. It is clear that I_m is significantly higher than I_c. In a specific application, I_m should be defined by the cooling requirement of the device. For example, if the dissipation caused by I_{Ag} = 1.0 A is less than the background heat leakage, it is probably acceptable to use I_m as the maximum operating current as we define here.

TABLE II

COMPARISON OF I_m (A) AND I_c (A) OF SINGLE- AND MULTIFILAMENT BSCCO-2223 PIT TAPES AT 77 AND 87 K[a]

Sample	77 K		87 K	
	I_m	I_c	I_m	I_c
Single-filament	25	15	15	7
Multifilament	48	35	30	23

[a] I_m is defined as total current at I_{Ag} = 1.0 A and I_c is defined as total current in an electric field of 1.0 μV/cm.

C. Melt-Cast BSCCO-2212 Rod

Fig. 7 shows a plot of V vs. I of a melt-cast BSCCO-2212 rod at 77 and 87 K. The critical current at 77 K is one order of magnitude larger than that at 87 K. The slope of the curve in Fig. 7 gives the resistivity of the BSCCO-2212 rod in the dissipative regime. Even though the critical current between 77 and 87 K differs significantly, the resistivity does not seem to vary a great deal over this temperature range.

IV. Summary and Conclusions

The flux-flow resistivity in terms of voltage vs. current of three high-temperature superconductors (a single-filament BSCCO-2223 PIT tape, a multifilament BSCCO-2223 PIT tape, and a melt-cast BSCCO-2212 rod) were measured at 67, 77, and 87 K. For silver-sheathed composite superconductors such as the BSCCO-2223 PIT tapes, current is shared between the BSCCO superconductor and the silver when the total transport current exceeds the critical current defined by the 1 μV/cm criterion. Two distinct regions are observed when the total current is increased. When the total current is $<I_m$, almost all of the current is in the superconductor and the current in the silver is zero. When the total current is $>I_m$, the current in the superconductor remains fairly constant and all of the excess current is transferred to the silver. In this region, the current in the silver increases linearly with the total current. We suggest that I_m, instead of I_c (defined by the 1 μV/cm criterion), is more appropriate for practical applications because I_m is based on actual cooling requirements.

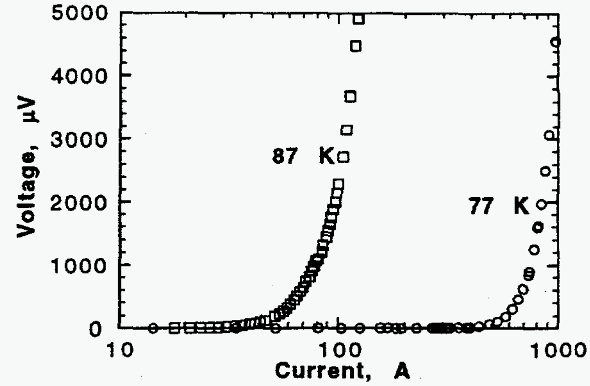

Fig. 7. Voltage vs. current of melt-cast BSCCO-2212 rod at 77 and 87 K.

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