SUPERCONDUCTING CURRENT LEADS OF YBCO AND Pb-BSCCO

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Abstract

We have fabricated and measured cylindrical superconducting current leads composed of a $Y_1Ba_2Cu_3O_7$ (YBCO) and $Bi_{2-x}Pb_xSr_2Ca_2Cu_3O_{10}$ (Pb-BSCCO), approximately 20 cm long and 1 cm^2 cross section . A steady state, dc, critical current of 170 (230) amperes at a temperature of 77 K was measured for YBCO (Pb-BSCCO) using a voltage criterion of 2×10^{-7} volts/cm ($\rho = 8 \times 10^{-10}$ ohm-cm). This current was limited by the current-induced, self magnetic field. At a temperature of 63 K this current increased to approximately 390 (465) amperes. The character of the magnetic field dependence of the critical current and the shape of the current induced voltage curves are different for the two materials.

Introduction

One of the most promising near term applications of high temperature superconducting materials is for current leads to low temperature superconducting magnets or in cryogenic power distribution systems. Such applications do not require particularly high critical current densities but they do require high currents. Current leads must carry high currents, but they are not required to be flexible and is there is no requirement to operate in high magnetic fields since the leads can be shielded from external fields. The purpose of the experiments reported here is to demonstrate the capability of $Y_1Ba_2Cu_3O_7$ (YBCO) and $Bi_{2-x}Pb_xSr_2Ca_2Cu_3O_{10}$ (Pb-BSCCO) to carry large dc supercurrents currents through large cross sections rather than large current densities in small area samples. Current leads to superconducting magnets will operate at temperatures between 4.2 K and 77 K. We have chosen to characterize our samples at the upper end of the temperature range, since this will be the most challenging region to achieve the required high currents and since one would prefer to operate power distribution systems at ambient liquid nitrogen temperatures or slightly above.

Sample and Experimental Setup

All samples were fabricated in the shape of cylinders with the following approximate dimensions: outer diameter, 1.6 cm; length, 20 cm; and cross section area, 1 cm^2. This shape was chosen to provide current flow in such a manner as to reduce the current induced self magnetic field which varies as 1/r where r is the distance from the cylindrical axis and to reduce the Lorentz forces between high current conductors. The length of the sample was chosen to demonstrate the ability to fabricate large structures, to provide a critical current measurement with sufficient sensitivity to be meaningful in an engineering sense, i.e., resistivities at the critical current several orders of magnitude less than cryogenic copper, and to provide ample room for lead attachment which require high area contacts at these high currents.

The YBCO sample was prepared by viscous processing techniques as described in previous publications[1,2]. The Pb-BSCCO sample was made by first weighing the individual cation salts in the ratio 1.84, 0.34, 1.91, 2.03, 3.06 respectively[3] and dissolving these salts in a nitric acid solution. The solution was then dried and the solid residue ground into a powder and repeatedly heated to 800 °C in air for 30 minutes with intervening regrindings. The resulting powder was pressed into a pellet and heated at 845 °C for 36 to 65 hours in a flowing $12N_2/O_2$ gas mixture, cooled at 1 °C/min to 700 °C and then cooled more quickly to room temperature. This pellet was reground and the powder was then poured into an annular mold consisting of an inner stainless rod and an outer rubber tube. This mold and powder were isostatically pressed (powder squeezed radially) to produce a cylindrical body with some degree of pressure induced orientation of the Pb-BSCCO platelets. The sample was removed from the mold and heat treated in a similar manner to the pellet mentioned above, except it was held at 845 °C for only 12 hours before cooling. X-ray diffraction and optical microscopy confirmed the sample to be predominantly the 2223 phase.

One of the major concerns in this experiment was the proper attachment of the normal current leads to the superconducting sample. At these high currents, large contact resistances can limit the observed critical current. To lessen this problem, we baked on (600 °C for 1 hr in flowing oxygen) either gold or silver contacts at each end of the cylinders, covering areas of approximately 10 cm^2 at each end. This area was subsequently "tinned" with a eutectic In - Ga solder. Concentric, coaxial current leads were used and attachment to the sample was made with copper braid which was flared to surround the ends of the superconducting sample. The resulting contact resistance ($\approx 10^{-3}$ ohms, but not accurately measured) was sufficient to produce no noticeable heating effects at 77 K where currents were limited to less than 250 amperes. At 63 K, with current levels over 500 amperes, contact resistance may have been a problem producing sample damage. Future research will focus on the issue of current insertion. In the tests reported here, the return flowing current was run through a copper rod coaxially located inside the cylindrical, superconducting sample. Voltage leads were attached to the superconducting cylinders, 10 cm apart and 4 cm from the current leads in order to conduct four terminal current voltage measurements on the superconducting samples. **Figure 1** shows a schematic of the cryostat, sample and lead arrangement.

Results

The samples were immersed in liquid nitrogen and the dc current was supplied using a Sorenson 800 ampere, 4 V power supply. The voltage was recorded analytically on an X - Y recorder and digitally in a Macintosh computer . The I - V curves were found to be reproducible and nonhysteretic. **Figure 2** shows some of the I - V curves taken at 77 K on these samples as a function of magnetic field, applied parallel to the cylindrical axis. The criteria for defining I_c was the point of first deflection from the zero voltage line which corresponded to a dc voltage criteria of about 2×10^{-7} volts / cm. The current - voltage curves can also be used to characterize the abruptness of the $I_c(H)$ transition using the empirical relation $V \sim I^n$ to fit the data. One can extract "n" values for the transition, as done previously for

Manuscript received September 24, 1990

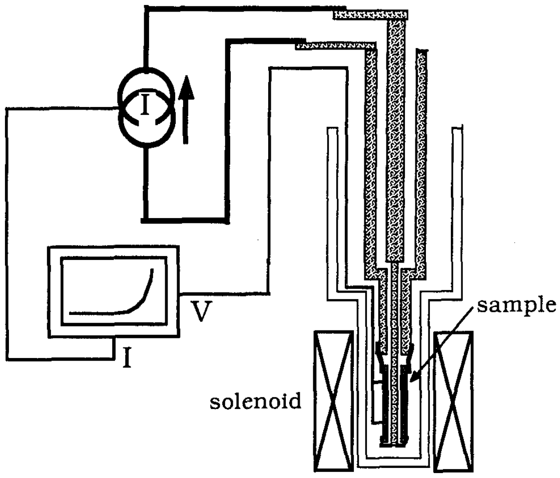

Figure 1. Cryostat and lead configuration for measuring I_c at temperatures between 77K and 63K.

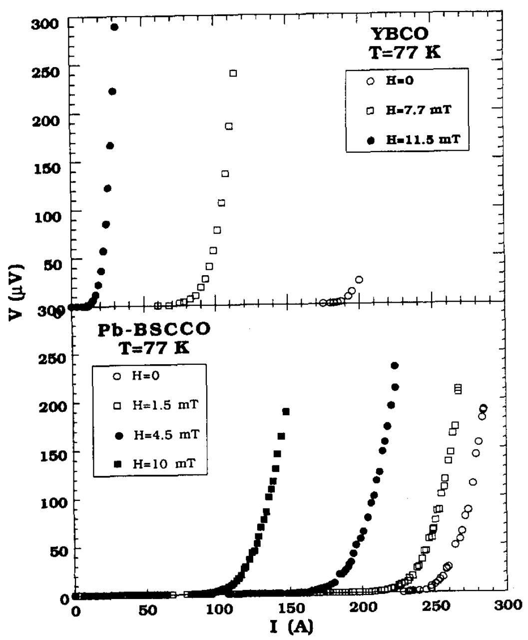

Figure 2. Voltage - current data for the YBCO (a) and the Pb-BSCCO (b) samples. Different data traces are shown at indicated magnetic field values.

both composite low temperature superconducting wires[4,5] and high temperature superconducting materials[1,6,7].

Figure 3 shows the results of our determination of I_c and "n" as a function of H for both YBCO and Pb-BSCCO. The zero field critical current is largest in the Pb-BSCCO (230 amperes compared to 170 amperes) but these values are of the same order of magnitude and vary somewhat with processing. Both YBCO and Pb-BSCCO have rapid reductions of I_c with field, but the functional form of $I_c(H)$ for the two materials is different. The fall off with H for the YBCO sample is characteristic of weak link behavior[6,7], while the fall off with H for the Pb-BSCCO sample is characteristic of weak flux pinning[8], functionally a $1/(H-H_0)$ dependency. The zero field I_c is, in fact, limited by the self field that is generated at the surface of the cylinder by the current[1]. For 200 amperes, the self field at the surface is about 5 mT.

The sharpest transitions occur in low magnetic fields, where "n" is 28 for Pb-BSCCO and 38 for YBCO. At higher fields the "n" values become markedly lower as the transition broadens, dropping to a value at 10 mT of 8 for the YBCO and 12 for Pb-BSCCO. Note that the "n" value does not fall as rapidly with H for Pb-BSCCO. Like the functional dependence of $I_c(H)$, both the functional dependence and the magnitude of the fall off of "n", n(H), is different for Pb-BSCCO compared to YBCO. Figure 4 demonstrates the differences between the two materials more dramatically by plotting the same data in a normalized manner. It is clear that flux pinning and flux dynamics are different in the two samples.

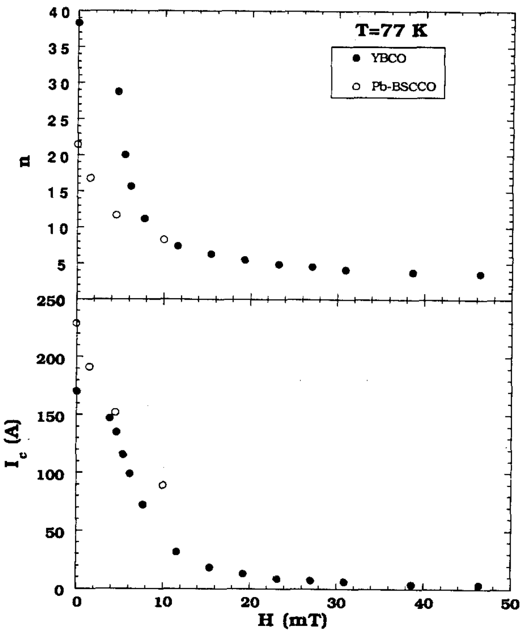

Figure 3. Comparison of normalized I_c and "n" values as a function of magnetic field for the YBCO and Pb-BSCCO samples.

Figure 5 shows the I-V plot for the same Pb-BSCCO sample taken at 63 K, the temperature achieved by pumping on the liquid nitrogen bath in which the sample was immersed. These data give an I_c of 465 amperes and an "n" value of 45. These two data points (i.e. I_c(77 K) and I_c (63 K)) extrapolate to I_c of zero at 91 K giving an "effective" T_c for the beginning of substantial critical currents. The T_c measured inductively for this material was 105 K. There is apparently a large (14K) temperature region where Pb-BSCCO is superconducting but supports only very small values of supercurrents. The same linear extrapolation of I_c to 4.2 K gives an I_c of 1500 amperes, which compares favorably with I_c values at 4.2 K deduced from magnetic shielding studies[9] on the same material.

Similar data was obtained on a different YBCO cylinder, which had different absolute values from those reported above, but which had similar magnetic field and temperature dependences with other YBCO samples. The T_c of this sample, determined by a linear extrapolation of the I_c data to zero, is 88 K, very close to the expected inductive T_c for this material. Thus the temperature where substantial currents can be attained

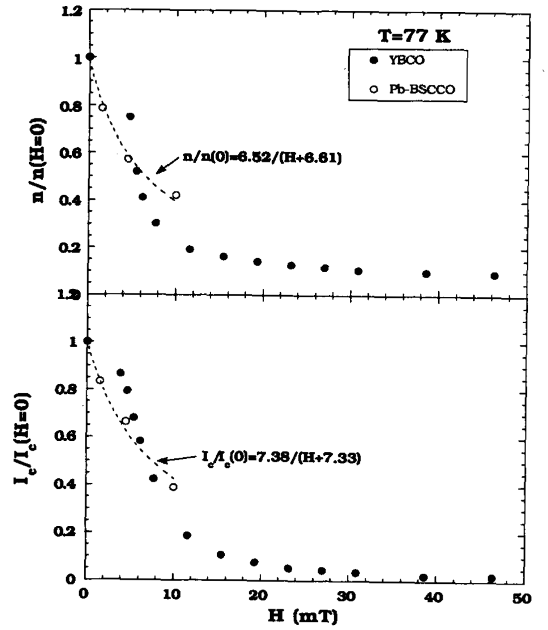

Figure 4. Comparison of $I_c(H)/I_c(0)$ and n(H)/n(0) values as a function of magnetic field for the YBCO and Pb- BSCCO samples. Data clearly show the different magnetic field dependences for the two materials.

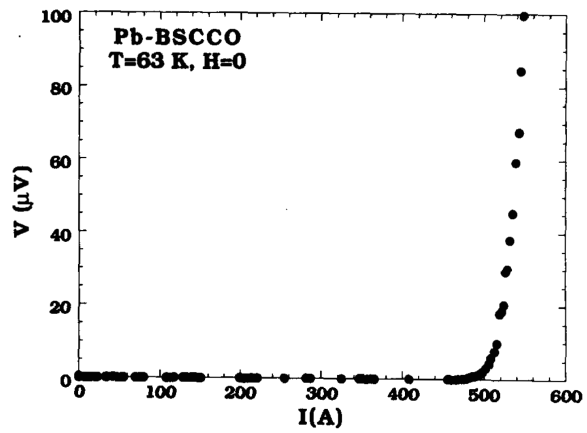

Figure 5. Voltage - Current curve for Pb-BSCCO sample at a temperature of 63K. Currents in excess of 500 amperes were passed through the sample, and the $I_c(63)$ was 465 amperes.

is near the superconducting transition temperature for YBCO samples. Interpolating from this YBCO sample to the YBCO sample reported above would give $I_c(63)$ of 390 amperes and $I_c(4.2)$ of 1300 amperes. This extrapolation again compares well with values deduced from magnetization studies[9].

In order to compare the temperature dependences of YBCO and Pb-BSCCO materials, we plot in **Figure 6** the normalized values of n(T)/n(77 K) and $I_c(T)/I_c(77$ K). From this data we deduce that the temperature dependences are similar. In both materials the critical current increased by approximately a factor of 2, while the "n" values increased by about 40%.

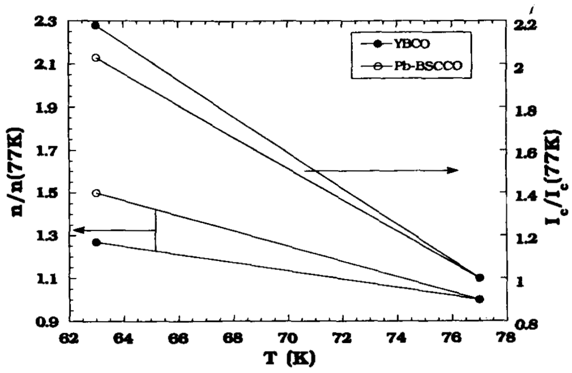

Figure 6. Comparison of $I_c(T)/I_c(77)$ and n(T)/n(77) values as a function of temperature for YBCO and Pb-BSCCO samples.

Discussion

In this article we report data showing that large supercurrents can be carried in bulk $Bi_{2-x}Pb_xSr_2Ca_2Cu_3O_{10}$ materials at liquid nitrogen temperatures and in zero magnetic fields. Comparisons between YBCO and Pb-BSCCO show that the two materials are comparable in their ability to carry large currents at 77 K. The limiting factor in both materials appears to be the current induced self magnetic field which rapidly degrades the performance. They differ, however, in the field dependence of I_c. Reasons for this difference need to be more fully explored, but appear to be associated with the differences between granular, weak link dominated behavior in the YBCO materials versus weak magnetic flux pinning sites in the Pb-BSCCO materials. It would appear that alignment is important to achieve high I_c in both materials.

Values of I_c approaching 500 amperes ($J_c \approx 500$ amperes/cm^2) have been achieved in Pb-BSCCO at 63 K. These data suggest that the superconducting properties of either Pb-BSCCO or YBCO are sufficient to design current leads to low temperature magnets at the present time. Rapid improvements are still expected as better processing leads to improved grain alignment, fewer weak links (YBCO) and stronger flux pinning (Pb-BSCCO).

Acknowledgements

This work was sponsored, in part, by SDIO and DARPA under their high temperature superconducting programs.

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