SWITCHING IN HIGH-T_c SUPERCONDUCTOR CURRENT TRANSPORT MEASUREMENTS*

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Abstract

Switching voltages can occur in four-wire current transport measurements of sintered high-T_c superconductors. These switching voltages are irreversible shifts in the voltage-current characteristic of the superconductor that result in multiple branches. The voltage along these branches can be very nonlinear as a function of current and can be positive or negative in polarity relative to the current direction. These voltages can interfere with the correct determination of resistivity and critical current density. Experimental data on unaligned sintered $Y_1Ba_2Cu_3O_{7-\delta}$ which illustrate the complex nature of the voltages and the confusion they can create are presented. Models based on weak links and H_{c1}, and on other effects, are discussed as are observations on NbTi and Nb_3Sn based superconductors.

Introduction

The voltage-current (V-I) characteristic of a superconductor represents the conductor's current-carrying properties.[1,2] The intrinsic voltage drop of a superconductor is a steady-state and reversible magnetic flux-flow voltage. For most superconductors, this characteristic can be approximated as

$$V = V_0 \ (I/I_0)^n, \qquad (1)$$

where V_0 is a reference voltage, I_0 is a reference current, and n indicates the steepness of the V-I curve. A typical value of n for a sintered-powder high-T_c sample in low magnetic field is 25. For most samples of this type, the n-values tend to decrease monotonically with increasing magnetic field to a value close to unity (ohmic) at a magnetic field of a few teslas and a temperature of 77 K.

An interfering voltage can be defined as a voltage that does not fit the ideal V-I relationship. If these interfering voltages are not accurately identified, misleading data will result. Interfering voltages can be either intrinsic or extrinsic. An extrinsic voltage does not represent the local properties of the superconductor. The interfering voltages observed in this paper are thought to be intrinsic voltages.

Many interfering voltages have a magnitude comparable to the intrinsic V-I characteristic of a superconductor. Most of these have been identified in NbTi- and Nb_3Sn-based superconductor measurements.[1-9] These voltages include thermoelectric (electromotive force), inductive (changing current with time), current transfer, ground loop, common mode, and ac voltages due to current ripple.

This paper extends the concept of several current redistribution phenomena[3-5] that are observed in multifilamentary NbTi and Nb_3Sn superconductor wires to sintered-powder high-T_c samples. A more complete description of these phenomena can be found in the references. Multifilamentary superconductive filaments in a normal matrix and anisotropic sintered-powder superconductor with convoluted superconductive percolation paths are nonlinear, highly anisotropic electrical conductors. Current in these conductors can result in voltages on the surface of the conductor that are positive or negative projections of resistive voltages within the conductor. The simplest example of this phenomenon is the voltage projections that arise from current redistributions among twisted multifilamentary superconductive filaments. The interactions of current injection, redistribution, and extraction create convoluted three-dimensional equipotential surfaces that result in non-monotonic voltages along the surface of the conductor.

The overall network of current percolation paths represents the collective response to the local properties, electromagnetic fields, and boundary conditions at current contacts. A nonlinear, anisotropic system is considered well behaved if the local properties do not change abruptly with time or current. In such a system, the initial current is divided among a number of current percolation paths. Additional percolation paths are separated from this first set by additional series resistance. For example in a multifilamentary superconductor, the current has to flow past the outer filaments and through additional series resistance to get to the inner filaments. Transfer of current to these additional paths requires a voltage drop in the first set of paths. As the current is increased, and the critical current density in these paths is exceeded, the current will be distributed among additional paths. In a well-behaved system, the total voltage drop increases monotonically with current. At all currents, the total voltage drop is minimized subject to current transfer limitations caused by the nonlinear, anisotropic conductivity.

An abrupt change in local properties (that is, not a well-behaved system) can lead to an abrupt change in the total voltage drop. In this case, the voltage drop for a segment of the conductor would shift or switch abruptly. The measurements presented in this paper suggest that some sintered high-T_c samples exhibit abrupt and hysteretic changes in local conduction properties. An abrupt change in the local properties may lead to a completely different network of current, and thus a completely different voltage characteristic.

Experimental Details

The voltage-current (V-I) curves were measured using two methods: a continuous current ramp (continuous method) where the current and voltage were measured continuously, and a stepped-current ramp (stepped method) where the current was ramped and held at various levels, and current and voltage were measured.[10] The results reported here have been observed with both methods; this implies a steady state effect. The continuous method lends itself to studying the complete V-I curve and current hysteresis.

All of the measurements reported here were made on straight, unaligned sintered $Y_1Ba_2Cu_3O_{7-\delta}$ (YBCO) samples immersed in liquid nitrogen at 76 K. Any applied magnetic field was perpendicular to the sample current. The current and voltage contacts were made

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using an ultrasonic soldering iron and In-2%Ag solder (no soldering flux). The samples did not have any cladding or solder contacts that formed a parallel path for the sample current. All samples were cooled in a field of less than $2x10^{-4}$ T. The uncertainty in the voltage measurements was ±5 nV ±2% of the signal. The uncertainty in the current measurements was ±0.2% of the maximum signal.

Experimental Observations

The type of interfering voltage presented here has been observed in many samples at many different voltages with both polarities. V-I curves of two sintered YBCO samples have been selected for presentation. These are representative of the observed phenomenon. All of the data presented were taken with zero applied magnetic field. In general, this phenomenon has been observed in measurements with magnetic fields as high as 0.1 T, but the amplitude of the switched voltage tends to decrease and become negligible at higher fields (lower currents).

Figure 1 is a plot of voltage versus increasing and decreasing current. These data were taken on a 1 x 1.8 x 11 mm YBCO sample that had been cut from a sintered pellet. The voltage taps were separated by 3.8 mm and the current contacts were 1.6 mm from the closest voltage tap. The initial portion of the V-I curve follows branch 1. There is an abrupt change in voltage as the current is increased above 0.8 A. The voltage goes from +1.3 μV to -0.2 μV, a change of about 1.5 μV. The V-I curve above this switching point is reversible along branch 2, to within the accuracy of the measurement, inductive voltages, and the time constant of the voltmeter. After this switching has occurred, if the current is decreased below 0.8 A, an entirely different characteristic is obtained, another branch of the V-I curve.

Many minor current loops (portions of the curve which were generated with increasing and decreasing current) were used to determine the limits of reversibility. There are two points on this curve where irreversibility occurs. One point is just above 0.8 A with increasing current. The other point is at or near zero current with decreasing current. In other words, branch 1 is retraced regardless of current ramp direction as long as the current remains below about 0.8 A. Once the current exceeds 0.8 A, branch 2 is retraced regardless of current ramp direction unless the current is reduced to near zero, in which case the V-I curve switches back to branch 1. This V-I characteristic remained unchanged through several ramping sequences designed to determine the limits of reversibility. At one point, the V-I characteristic changed to one that would occasionally switch from branch 1 to branch 2. If it did not switch to branch 2, it would continue along branch 1 and have a sharply increasing voltage just above 1.2 A (not shown in the figure) instead of that observed on branch 2 near 1.5 A. This change would represent a 20% difference in the critical current.

Figure 2 shows another example of this type of behavior on another YBCO sample which was 1 x 1.7 x 16 mm. The voltage taps were separated by 3.6 mm and the current contacts were 3.5 mm from the closest voltage tap. In this case the initial increasing current curve, branch 1, goes to a negative voltage until a switching phenomenon occurs near 0.75 A. The change in voltage was about 0.2 μV at the switch point. Except for the opposite polarity, this characteristic has similar points of irreversibility at 0.75 A and near zero current. In both figures, the shape of branch 2 is more conventional than that of branch 1.

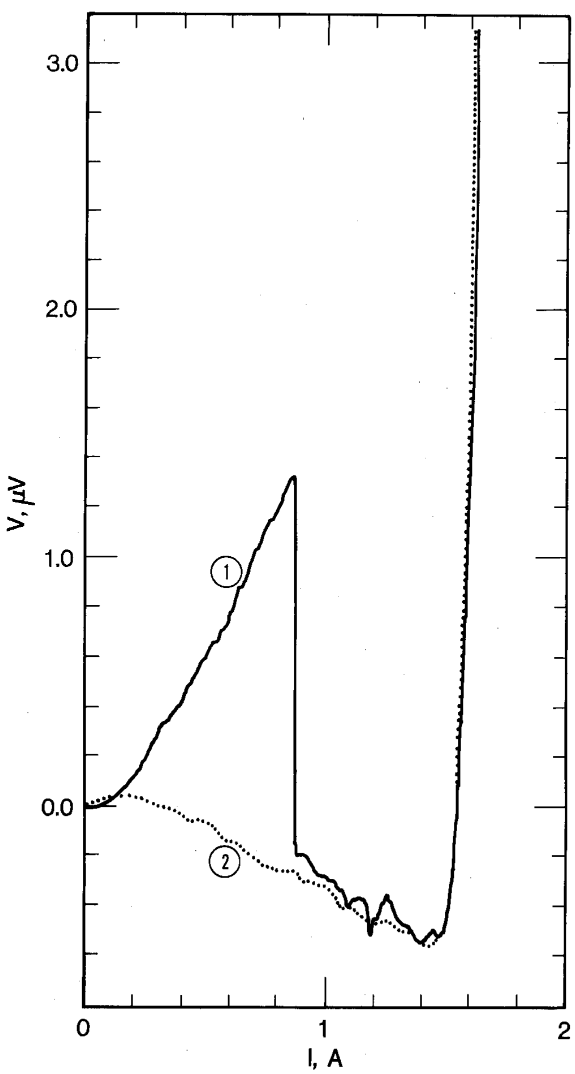

Figure 1. Plot of voltage versus increasing and decreasing current with initial branch indicated as 1 for a sintered YBCO sample.

The amplitude of this voltage switch decreased with repeated curves. However, the original amplitude returned after the sample was warmed above its transition temperature and re-immersed in liquid nitrogen. The amplitude of the switch remained fairly constant for more than 15 major and minor current loops.

A number of sintered samples that exhibit small switching voltages have been studied. In some samples, switching occurs at multiple currents along the V-I characteristic. Also, on a given sample, the switching can be positive or negative in polarity. None of the thin-film samples that have been measured have exhibited voltage switching. No aligned bulk samples have been measured.

The sintered high-T_c samples were relatively short compared to their cross-sectional dimensions, leading to possible complications due to the proximity of the voltage taps to the current contacts. In fact,

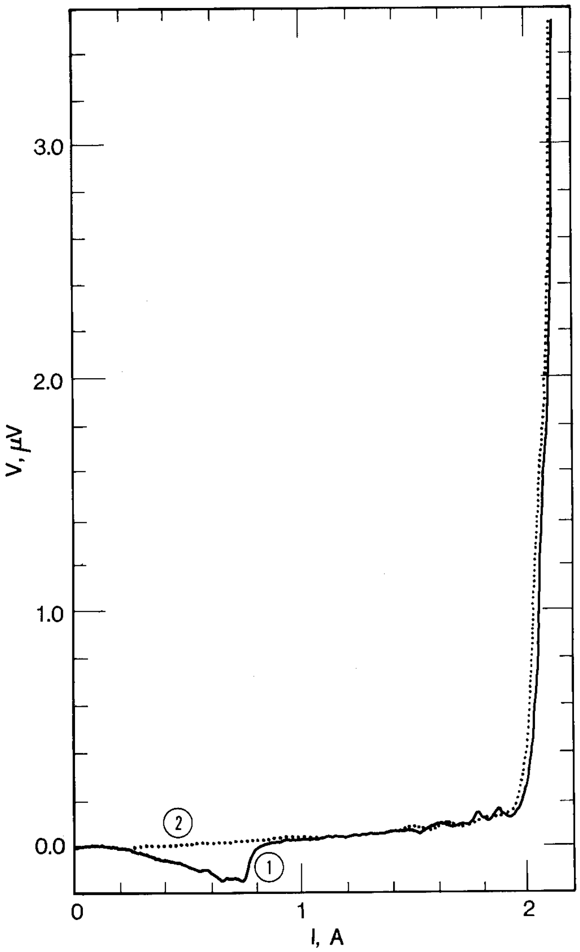

Figure 2. Plot of voltage versus increasing and decreasing current with initial branch indicated as 1 for a sintered YBCO sample.

this switching phenomenon would have been dismissed if observations had not been made on much longer specimens. This phenomenon has been observed in sintered YBCO samples that were 0.86 mm in diameter and 34 mm long with voltage tap separations of 9 mm and current contact to voltage tap separations of at least 8 mm.

Thermoelectric voltages and sample heating caused by current contact resistance is not expected to be the source of the switching voltages, since these voltages have been observed over a range of currents, magnetic fields, and contact resistances. For Figure 1, the power dissipation of the two current contacts was about 0.1 W at 0.8 A with a heat flux of less than 0.6 W/cm^2. For Figure 2, the power dissipation of the two current contacts was about 0.05 W at 0.75 A with a heat flux of about 0.3 W/cm^2. The heat flux at the current contacts is low compared to the 15 W/cm^2 where liquid nitrogen goes from nucleate to film boiling. Therefore, the temperature of the sample should be close to the bath temperature. Also, a threshold above which these voltages would decrease in magnitude does not seem feasible for a heating mechanism. The switching voltages may correlate with contact resistance, since a higher contact resistance may indicate a more local current injection. Thus, some percolation paths would be preferred over others.

Phenomenological Models

The electromagnetic properties of sintered superconductors are not well understood. The sharp change in voltage, magnetic field dependence, and the noted reversibilities and irreversibilites are quite distinctive. An understanding of the physics of equipotential surfaces in superconductors[5] and the origin of negative voltages[4] in superconductors are prerequisites to understanding the models presented here. There are some common elements of these models: the conductor is approximated by some network of current paths, there is a physical mechanism for changing the local properties, and this change needs to be hysteretic and collective.

Redistribution of magnetic flux is the hysteretic and collective element of the phenomenological models described here. Redistribution of flux could cause a change in the local properties which would change the voltage profile. Redistribution of flux could also cause a redistribution of current or change the network of current percolation paths. If the redistribution of the flux, associated with H_{c1}, or the motion of a flux bundle is collective, then the associated change in voltage profile will be abrupt. The fact that the magnitude of these voltage switches decreases with applied magnetic field suggests that H_{c1} may be the collective element. It is expected that the voltage would decrease as the sample current decreases with increasing applied magnetic field.

The physical mechanism for changing the local properties for the first model assumes that the conductor consists of a network of weak-linked regions and regions of good superconductor, each with a different H_{c1}. These weak-linked regions form a network of paths for the magnetic flux lines to traverse the sample under the action of the Lorentz force. The lower H_{c1} and low pinning of the weak-linked regions will result in flux-flow voltage at a low current. As the current and associated magnetic field increase, there is a point at which the magnetic flux enters the good regions which are adjacent to the weak-linked regions. Thus, flux can be pinned adjacent to these weak-linked regions, consequently pinning the flux in the weak-linked regions through magnetic interaction (flux line shear). As a result, the absolute value of the voltage drop along the sample decreases. If the current is decreased below this flux redistribution point, a different branch of the V-I curve, branch 2, is obtained because of the hysteresis of the pinned flux. At some lower current, the flux will leave its pinning site and branch 1 will be retraced if the current is increased. Notice that the V-I curve obtained with decreasing current is more conventional and is absent of voltage switches. There may be a probability associated with whether or not this switch occurs depending upon the details of where the flux is pinned. This would explain how a sample's V-I curve, like that shown in Fig. 1, could stay on branch 1 and give a significantly lower I_c.

Another mechanism for changing the local properties assumes that the current starts to flow through a preferred or first set of current percolation paths. Additional percolation paths are separated from this first set by a resistive barrier. Transfer of current to the additional percolation paths through the barrier requires a voltage drop in the first set of paths. The barrier resistance may be nonlinear with respect to currents and have a higher resistance at the lower currents. This semiconductor-like behavior would result in a lower voltage drop after the current starts flowing through the barrier. Thus, the voltage observed on the voltage taps may decrease significantly when additional paths start to carry current.

Elements of these models could be applied to a network of Josephson junctions. This network would be affected by the distribution of trapped magnetic field flux. It may also be possible for a network of micro-cracks to create this phenomenon where voltage, current, or electromechanical thresholds are exceeded.

Discussion

This switching voltage or multivalued-I_c phenomenon is not observed in all sintered-powder high-T_c samples. A collective phenomenon is necessary in order to have an abrupt and significant switching. This requires a degree of homogeneity. If there are a number of small switches, they could be below detection limits or be considered voltage noise.

The presence of this phenomenon shows that the critical current may be multivalued depending on the choice of criterion and could be increased by going to higher currents. It is well known that I_c can be significantly increased or decreased through cycling the applied magnetic field to higher levels.[2] However, this study addressed changes in I_c during a single V-I curve. Furthermore, this study showed an increase in I_c at zero applied magnetic field; in contrast, cycling an applied magnetic field results only in a decrease in I_c at zero field. It may be possible to achieve higher critical currents at all magnetic fields through pulsing the sample to higher currents and shifting the resulting dc V-I characteristic to higher currents. This would reduce the effect of sample heating during the training to higher currents. The trapped self-magnetic field lines might give an enhanced effect over trapped applied-magnetic field lines, since the self-field has a more appropriate geometric shape. The self inductance of the sample or a concentrated current distribution could also increase the local magnetic self-field. It may be that the V-I characteristic would revert to the lower current curve after the applied current was decreased. This training effect using pulsed currents has not been observed in preliminary investigations.

These voltages are analogous to current transfer voltages, but they seem to disappear at the higher currents. Therefore, these voltages should not be subtracted from the V-I curve as is commonly done for current-transfer voltages in NbTi- and Nb_3Sn-based superconductors.

In general these results indicate the need for careful measurement of sample voltage near the intrinsic flux-flow voltage region of the V-I curve. The V-I curve generated with decreasing current may be a better measure of the properties of the superconductor.

Conclusions

Switching voltages can interfere with the accuracy and precision of critical-current measurements, they may limit the direct measurement of the upper limit to the resistivity of sintered $Y_1Ba_2Cu_3O_{7-\delta}$ and other high-T_c materials in the superconducting state, and they may affect some applications of these materials. Measurements of the voltage-current characteristics with increasing and decreasing currents will identify this effect and curves generated with decreasing current may be more accurate. The presence of this phenomenon suggests that the critical current may be multivalued and could be increased by going to higher currents.

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