Flux Dynamics and Time Effects in a Carved out Superconducting Polycrystalline Bi-Sr-Ca-Cu-O Sample

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Abstract: Systematic slow transport relaxation (V-t curves) and magnetovoltage measurements (V-H curves) have been carried out in a carved out superconducting polycrystalline Bi-Sr-Ca-Cu-O sample as a function of current (I), temperature (T), and external field (H). The V-t curves reveal the details of the time evolution of the penetrated state within the granular structure of the sample and also give a direct evidence of the relaxation of the flux trapped inside the drilled hole on the time scale of the experiment. On the other hand, V-H curves exhibit several unusual interesting properties upon cycling of the external magnetic field in forward and reverse directions, and, in addition to irreversibilities, strong reversible effects are observed, which is associated with the trapping of the macroscopic flux bundles in the drilled hole. It is also observed that the field sweep rate influences dramatically the reversible and irreversible behavior of V-H curves. The experimental results were mainly interpreted in terms of current and field induced organization of the vortices.

1. Introduction

The interplays between pinning and depinning and short and long range correlations in the vortex structure of a type-II superconductor cause a wide range of phenomena such as dynamic instabilities, relaxation and memory effects, irreversibility, glassy relaxation etc. [1]. Response of flux lines to an applied current (i.e., current driven organization) could be monitored by slow [2] and fast transport relaxation measurements [3] via time (t) evolution of sample voltage (V), i.e., V-t curves. In addition, the dynamic and static properties of vortex structure through the superconducting sample are investigated by means of magnetoresistance [4] and magnetization measurements [5]. In this study, the flux dynamic in a polycrystalline sample of Bi1.7Pb0.3Sr2Ca2Cu3Ox (BSCCO) with a cylindrical hole (CH) drilled with a diameter of 0.5 mm (referred as sample A) and a BSCCO sample without hole (referred as sample B) are investigated by the transport relaxation (V-t curves) and magneto-voltage (V-H curves) measurements.
2. Experiment

A Bi$_{1.7}$Pb$_{0.3}$Sr$_2$Ca$_2$Cu$_3$O$_x$ sample has been prepared from the high purity powder of B$_2$O$_3$, PbO, SrCO$_3$, CaCO$_3$ and CuO by using the conventional solid state reaction. dc electrical resistivity measurements have been carried out using a standard four point method. The BSCCO sample in the form of slab for the transport measurements is in the dimensions of length $l \sim 6.35$ mm, width $w \sim 3.4$ mm, thickness $d \sim 1.3$ mm. The pure copper wires for the voltage and currents pads were attached by silver paint. During the experiments, a temperature stability better than 10 mK has been maintained. The current source Keithley-6221 and the voltmeter Keithley-2182A with a resolution 1nV are used to apply current and to read low voltage levels, respectively. The BSCCO sample whose results are presented in this work has the zero resistance at $\sim$105 K. The magnetic field was generated by an electromagnet. In V-H curves, the external magnetic field ($H$) was oriented perpendicular to the transport current ($\mathbf{I} \perp \mathbf{H}$).

3. Results and discussion

A dc driving current, $I_1$, is applied to the sample for a while (i.e., 60 s), and, then, changed from $I_1$ to a lower value of $I_2$, kept constant during the relaxation process. Figure 1a shows such typical V-t curves for sample A measured for $I_1$=20 mA and different current values of $I_2$=0, 2, 4, 6, 8, 10, 12, 14, 16, and 18 mA for zero field at $T$=102 K. It is observed that the sample voltage increases non-linearly and tends to saturate in time interval of 0-60 s before the initial current $I_1$ is reduced to a finite current value or interrupted completely. When $I_1$ is reduced abruptly to a certain value of $I_2$, it is seen that, after a sharp drop, the sample voltage associated with the quenched state decreases over time. The decrease in voltage is not completely smooth, but, evolves in the form of steps as the time progresses. In addition, at early times of the relaxation process, a voltage hump which becomes more significant below 10 mA appears. Similar V-t measurements were repeated for sample B at 102 K. Figure 1b represents typical V-t curves measured for the current values of $I_2$=15, 30 and 35 mA at zero field. The initial current $I_1$ was taken as 40 mA. We suggest that the non-linear growth in voltage given in zero field V-t curves of Sample A and B can be considered as a reorganization of the transport current in a multiply connected Josephson network. That is, the physical case...
can be related to the increase in the formation of resistive flow channels in the volume of sample as the time progresses. [6] In Fig.1b, it is observed that a steady state evolves for \( I_1 \). This can be attributed to the fact that the transport current nearly completes the redistribution process in the time interval of 0-60 s, whereas, it was observed for sample A [see Fig.1a] that the voltage still tends to increase over time. We suggest that the dynamic process concerning the penetration of driving current (for sample A) is still active and can be related to the contribution of the trapped flux in CH to the measured dissipation. On the other hand, after \( I=I_2 \), the step behavior and the difference between the \( V-t \) curves of samples A and B can be correlated to the gradual decrease in the flux stored in CH of sample A.

We now show that the decrease in voltage at the currents of \( I_2 > 8 \) mA in Fig.1a can be described by an empirical relation of \( V(t) \sim \exp(-t/t_o) \) which is analogous to glassy state relaxation [4]. Here, \( t_o \) is the characteristic time. Solid lines in Fig.1a and Fig.1b represent the curves calculated by using \( \exp(-t/t_o) \). However, below 10 mA, the \( V-t \) curves give more reasonable agreement with an empirical relation of \( V(t)\sim 1/[1+(t/t_o)^2] \) [2] rather than the one using \( \exp(-t/t_o) \) [see the dashed lines in Fig.1a]. This expression describes well the voltage hump at onset of the relaxation process. The dotted lines in Fig.1a show the calculated curves of logarithmic relaxation \( V(t)\sim \ln(t/t_o) \). Note the large deviation between the data and \( \sim \ln(t/t_o) \) behavior.

Figures 2a show the magnetovoltage (\( V-H \) curves) measurements taken for different field sweep rates of \( \frac{dH}{dt} \) at \( I=15 \) mA and \( T=94 \) K in sample A. It is seen from Fig.2a that the measured dissipation depends strongly on \( \frac{dH}{dt} \). This implies that the variation of \( \frac{dH}{dt} \) serves to control the number of flux lines inside the sample and also inside CH. Further, the large difference between measured dissipations corresponding to \( 1 \) mT/s and \( 3 \) mT/s, respectively, can be explained as follows: at low sweep rates, the flux lines find enough time for penetration, and, thus, an increase in the number of flux lines joining the motion causes an enhancement in the measured dissipation.

Figure 2b shows the \( V-H \) curves corresponding to the sample B for \( \frac{dH}{dt} = 1 \) and \( 3 \) mT/s at \( T=94 \) K and \( I=50 \) mA. It is seen that the \( V-H \) curves are independent of sweeping rate of field so that they collapse nearly on the same curve. This suggests that, due to the weak pinning properties of sample B, the increase in field can be comparable to the time needed for the flux lines to move in the medium. In addition, the \( V-H \) curves in Fig.2b reveal typical clockwise hysteretic curves (forward region) for high
temperature superconducting samples [6]. We suggest that the hysteresis effects are mainly related to the return flux going through the grain boundaries and generated by the trapped field in the grains [7]. This could explain the usual clockwise hysteretic effects in Fig.2b. However, in Fig.2a, the $V-H$ curves show counter clockwise behavior which is unusual, which can originate from the trapped flux in CH of sample A.

A normal region in the form of a cylinder (metallic or insulating) or a cylindrical hole attracts the flux lines since a flux line will try to save core energy when it is centered at the defect, provided that the radius of the defect ($r$) is greater than the effective coherence length ($\xi$) i.e. $r > \xi$. Mkrtchyan and Schmidt [8] showed that the number of maximum flux lines which can be trapped inside the columnar defect, which is the empty cylindrical cavity, is proportional to $\sim r/2\xi$. In our case, the radius of CH (i.e., $r = 0.25$ mm) drilled in the BSCCO sample is sufficiently greater than $\xi$. Thus, it should present an attractive potential energy to an incoming flux line, and, thus, will trap many flux lines. As the field is decreased, we suggest that a repulsive interaction between the trapped flux inside CH and the ones out of CH in the sample can evolve, which prevents the flux trapping in the volume of the sample. Such a case will enhance the measured dissipation. Further, due to the field gradient, the trapped flux in CH can penetrate the sample behaving as a flux source. In addition, the field sweep rate dependence shows that the number of the flux lines inside the sample and CH for each $V-H$ curve is not equal to each other. As $dH/dt$ decreases, the effective number of flux lines through the sample A increases, so that it brings strong reversible behavior observed in $V-H$ curves.

4. Conclusion

In this study, the flux dynamic in a polycrystalline sample of $\text{Bi}_{1.7}\text{Pb}_{0.3}\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_x$ with a hole drilled was investigated by the $V-t$ and $V-H$ curves. The results were compared to that of the sample before drilling a hole and were interpreted in terms of current and field induced organization of the vortices and flux trapping in the volume of the sample.

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