Magnetovoltage Measurements and Field Sweep Rate Dependence of \( V-H \) curves in Superconducting Polycrystalline \( Y_1Ba_2Cu_3O_{7-x} \)

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Abstract: Magnetovoltage measurements (\( V-H \) curves) were carried out in superconducting polycrystalline bulk \( Y_1Ba_2Cu_3O_{7-x} \) (YBCO) material as a function of current (\( I \)), temperature (\( T \)), field sweep rate (\( dH/dt \)) and field orientation with respect to the transport current. A relative decrease in the dissipation measured in \( V-H \) curves was observed as \( dH/dt \) is increased, which implies that the time spent to plot the whole cycle has an importance on the evolution of the \( V-H \) curves. Thus, it could be possible to observe the relaxation effects in magnetovoltage measurements. In addition, the several significant steps and plateaus in \( V-H \) curves evolve depending on the magnitude of the transport current and also \( dH/dt \). These observations were attributed to locking of the flux lines to decrease or increase in size of the easy motion flow channels. The strong hysteresis effects in \( V-H \) curves were discussed mainly by means of the flux trapping within the granularity of sample and the different degree of the inhomogeneous flux motion with respect to the sweeping of the external magnetic field up and down.

1. Introduction

The transport and magnetization measurements of polycrystalline High-\( T_c \) Ceramic Superconductors (HTSCs) together with strong irreversibilities appearing in flux dynamics show a complex behavior which arise from the presence of duality in their superconducting properties, i.e., presence of weak-links and network of strongly superconducting grains embedded in background of weak-link structure. Therefore, low and high field strong irreversibilities seen in polycrystalline HTSCs samples are mainly interpreted in terms of flux trapping evolving in both intergranular and intragranular regions [1-3]. Two-level critical state model proposed by Ji et al. [1] explains the magnetic hysteretic effects and microwave losses by calculating the macroscopic and local fields along percolative paths through the grains for ordered and disordered polycrystalline samples. Another recent model developed Beloborodov et al. [4] gives a reasonable agreement with the experimental results concerning the negative magnetoresistance observed in granular superconducting Al sample [5]. Very recently,
Palau et al. [6] have shown experimentally that the irreversibility effects arise from the return field from grains into the grain boundaries.

In this study, magnetovoltage measurements ($V$-$H$ curves) were carried out as a function of parallel and perpendicular magnetic field ($H$) orientations with respect to the transport current ($I$) (i.e., $H//I$ and $H\perp I$), temperature, the magnitude of transport current, and sweep rate ($dH/dt$) of the external magnetic field in polycrystalline bulk sample of $Y_1Ba_2Cu_3O_{7-x}$ (YBCO).

2. Experiment

YBCO sample has been prepared from the high purity powder of $Y_2O_3$, $BaCO_3$ and $CuO$ by using the conventional solid state reaction. Magnetovoltage measurements were carried out using standard four point method and performed in a closed cycle refrigerator. The current source Keithley-6221 and Keithley-6182A are used to apply current and to read low voltage levels with a large precision, respectively. The magnetic field was generated by a conventional electromagnet. The YBCO sample whose results are presented in this work has the zero resistance at ~92 K with a transition $\Delta T_c$ of about 3 K at $H=0$.

3. Results and discussion

Figure 1 represents the $V$-$H$ curves measured at 86.5 K for the current values of 30 and 60 mA. The $V$-$H$ curves were obtained for the field sweep rate of $dH/dt = 5$ mT/s in a field range of 0-60 mT. The dashed and solid lines in Fig.1 correspond to the curves where $H//I$ (longitudinal $V_{\parallel}$) and $H\perp I$ (transverse $V_{\perp}$), respectively. The $V_{\parallel}$ and $V_{\perp}$ curves increase nonlinearly with increasing of the external magnetic field and tend to nearly saturate after the certain field value. It is seen that the measured dissipation in $V_{\parallel}$ and $V_{\perp}$ curves are comparable. This suggests that there is no force free configuration for polycrystalline samples, so that the condition of $H//I$ can not be satisfied in polycrystalline samples on the macroscopic average by giving rise a finite angle between $H$ and $I$ due to the defects and layered structure of YBCO. The $V$-$H$ curves in Fig.1 exhibit small steps and relatively large plateaus appearing in the increasing and decreasing branches of hysteresis loops. We attribute the steps and plateaus to several dynamic phases developing inside the sample and to locking of the flux lines to decrease or increase in size of the easy motion flow channels. In the figures, the arrows show the direction of sweeping of the magnetic field.

Figure 2 shows the influence of the sweeping rate of external magnetic field on the evolution of $V_{\perp}$ curves at 82.7 K. The measurements were carried out at the currents of $I = 60$ and 30 mA for $dH/dt=1$ and 5 mT/s, respectively. For this temperature range and also the current values, it is seen that the measured dissipation for $dH/dt=5$ mT/s is lower than that of $dH/dt=1$ mT/s. On the other hand, several steps and plateaus appear for $dH/dt=1$ mT/s, whereas, for $dH/dt=5$ mT/s, the $V$-$H$ curves become more smooth as compared that of $dH/dt=1$ mT/s.

It can be suggested that, at high sweep rates, the increase in field can be faster than the time needed for the flux lines to move. In this case, the flux lines will not find enough time to lock to a state for a long time and thus smooth hysteresis loops will be obtained. We also note that the area of the hysteresis loops for each current value is nearly the same for both sweep rates and the shape of hysteresis loops is not affected by the variation of $dH/dt$. Relative increase in dissipation at low sweep rates seen in Fig. 2
can be explained as follows: At low sweep rates, the vortices find enough time to relax and reach an equilibrium configuration. Thus, measured dissipation decreases relatively.

**Figure 1.** Evolution of $V$-$H$ curves measured for $I=30$ and 60 mA at 86.5 K for $dH/dt=5$ mT/s. Solid lines correspond to $\vec{H} \perp \vec{I}$, whereas, the dashed lines represent $\vec{H} \parallel \vec{I}$.

**Figure 2.** Sweep rate dependence of the $V$-$H$ curves for $I=30$ and 60 mA at 82.7 K. The solid lines represents the $V$-$H$ curves measured for $dH/dt=1$ mT/s and the dashed lines refer to the $V$-$H$ curves measured for $dH/dt=5$ mT/s.

Figure 3 shows a set of $V_\perp$ curves measured at 81.5 K for different current values of $I=30, 40, 50, 60, 70,$ and 75 mA, respectively. In the measurements, the magnetic field was swept in forward and reverse directions for $dH/dt=2$ mT/s. It is seen that the $V$-$H$ curves evolve in the shape of a butterfly due to the change in the direction of the external magnetic field. As the field is increased ($H^{\text{up}}$) or decreased ($H^{\text{down}}$) in both forward and reverse directions, the measured dissipation appears after and before a critical value of $H$ called $H_c^{\text{up}}$ and $H_c^{\text{down}}$, respectively.

The experimental $V$-$H$ data reveal that $H_c^{\text{up}}$ and $H_c^{\text{down}}$ depend on the magnitude of the applied current. Figure 4 depicts such a dependence extracted from the sweeping of the magnetic field in forward direction. Fig.4 shows that both $H_c^{\text{up}}$ and $H_c^{\text{down}}$ decrease with increasing of the transport current and the variation of $H_c^{\text{down}}$ with $I$ is more prominent than that of $H_c^{\text{up}}$, i.e., $H_c^{\text{down}}>H_c^{\text{up}}$. According to the two level critical state model [1], when $H$ is decreased with a certain rate, the flux trapped in the grains provides a field opposite to the external magnetic field in the grain boundaries so that the effective local field in the grain boundaries can be reduced. Thus, especially at low currents, since the pinning is more effective, $H_c^{\text{down}}$ would be much greater than $H_c^{\text{up}}$. The difference between $H_c^{\text{up}}$ and $H_c^{\text{down}}$ can be attributed to a measure of hysteresis effects. We suggest that the hysteresis effects appearing in $V$-$H$ curves arise from the flux trapping in the grains [1-3]. In decreasing branch of $V$-$H$ curves, a considerable decrease in the effective local field compared to that of the increasing branch can develop due to the return flux going through the grain boundaries and generated by the trapped field in the grains [6,7], which leads the hysteresis effects in magnetovoltage curves. This explains also the symmetry of the $V$-$H$ curves where the field is cycled forward and reverse directions, i.e., between $+H$ and $-H$. 
Figure 3. $V$-$H$ curves measured at $I=30, 40, 50, 60, 70,$ and $75$ mA at $T = 81.5$ K for $dH/dt = 2$ mT/s. The magnetic field is swept in forward and reverse directions.

Figure 4. Current dependence of critical field values $H_{c}^{up}$ and $H_{c}^{down}$ extracted from the $V$-$H$ curves given in Fig. 3.

4. Conclusion

In this study, magneto-voltage measurements ($V$-$H$ curves) were carried out in polycrystalline superconducting sample of $Y_{1}Ba_{2}Cu_{3}O_{7-x}$ (YBCO). The strong hysteresis effects in $V$-$H$ curves were interpreted mainly by means of the flux trapping within the granularity of sample and the different degree of the inhomogeneous flux motion with respect to the sweeping of the external magnetic field up and down. Sweep rate dependence in $V$-$H$ curves was attributed to less relaxation effects evolving in the grains and more effective trapped field, and, thus, more return flux and less effective field at the grain boundaries.

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