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History effects in low-field magnetoresistance of BPSSCO polycrystals

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Abstract. Low-field ($H < 40$ G) magnetoresistance measurements have been made on $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_{10}$ polycrystals at several temperatures between 80 and 105 K. Considerable hysteresis in $\rho(H)$ is found in a zero-field-cooled sample when the applied field is increased from 0 to a maximum value and then lowered back to 0 at all temperatures. The observation of hysteresis is taken as an evidence for field trapping in the grains. We show that the hysteresis in $\rho(H)$ occurs for applied fields much lower than that at which $d\rho(H)/dH$ exhibits a discontinuity. In addition, we find that when the applied magnetic field (H_a) is lowered from a maximum field, the effective intergranular field, H_{eff}, becomes zero for $H_a > 0$, which gives rise to a minimum in $\rho(H)$.

Keywords. Magnetoresistance; hysteresis; high-T_c superconductor; BPSSCO.

1. Introduction

Polycrystalline samples of high-temperature superconductors (HTSC) are generally recognized as granular superconductors. They consist of superconducting grains coupled by weak links. The current induced dissipation in the superconducting state is governed by the presence of two types of current, viz. the intergrain current and the intragrain current. The low value of bulk J_c measured in these systems and its reduction by about two orders of magnitude in low fields ($H < 100$ Oe) has been described by a model describing Josephson type of coupling between the grains (Peterson and Ekin 1988).

It is observed that a zero-field-cooled (ZFC) sample in applied field exhibits strong hysteretic effects in J_c (Evetts and Glowacki 1988), AC susceptibility (Levy *et al* 1993), magnetoresistance (Pradhan A K, unpublished), and higher harmonics in magnetization (Shailendra Kumar *et al* 1992). The hysteresis in these is attributed to the field in the intergranular region, H_{eff}, which is determined by the grain magnetization and therefore depends on the history. It is of importance to note that at a given temperature, hysteretic effects are observable only when the maximum applied field, H_m, is such that the field is trapped in the grains.

Lopez *et al* (1992) have made magnetoresistance measurements on a polycrystalline $GdBa_2Cu_3O_7$ sample to obtain the $H_{c1g}(T)$. They identify H_{c1g} with the field at which a discontinuity is obtained in the plot $dR(H_a)/dH_a$, in ZFC sample. The argument following this result is that as we increase the field from 0, in a ZFC sample, for $H_a < H_{c1g}$, the field lines are concentrated in the grain boundaries. Therefore, $R(H_a)$ has strongest field dependence here and when $H_a > H_{c1g}$ the intensity of the induction field in the junction is reduced as a result of which a drop in rate of increase in magnetoresistance is observed, and therefore the discontinuity in $dR(H_a)/dH_a$.

We report here low-field magnetoresistance measurements on a polycrystalline $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_{10}$ sample at various temperatures and show that hysteresis in $R(H)$ exists at fields far below the peak in $dR(H_a)/dH_a$. This implies that flux penetrates into the grains at a field much lower than is evident from the suggestion of Lopez *et al* (1992).

2. Experimental

Samples in the form of pellets of nominal composition $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_{10}$ were prepared in the standard ceramic route. For resistance measurements the samples used were of dimension $10 \times 1.1 \times 1.49$ mm. Four probe contacts were made by Indium solder and the contact resistance was $< 5\,\Omega$. A constant AC current of 1 mA at 23·1 Hz was passed through the sample. The voltage was sensed by a lock-in amplifier (SRS 530) with a low noise transformer (EG and G PAR 1900) at the input stage. The temperature was measured by a $100\,\Omega$ Pt. resistance driven by a 1 mA dc current from a constant current source (Keithley 224) and the voltage sensed by a DMM (Keithley 196). Temperature was maintained constant within ± 0.05 K at each temperature.

3. Results and discussion

The resistivity at room temperature of the sample is $2.54\ m\Omega\,cm$. Figure 1 shows the variation of resistivity, ρ as a function of temperature, T, between 80 and 200 K, for $I = 1$ mA. The variation is linear in T above 130 K. Significant departure from linearity occurs at $T_c(\text{on}) \simeq 120$ K. Between 113 and 105 K the rate of decrease in ρ is fairly sharp. Below 105 K the fall is gradual, i.e. it tails off to finally achieve a $T_c(\text{zero})$ at 98 K. Similar tails in $\rho(T, H = 0)$ have been observed

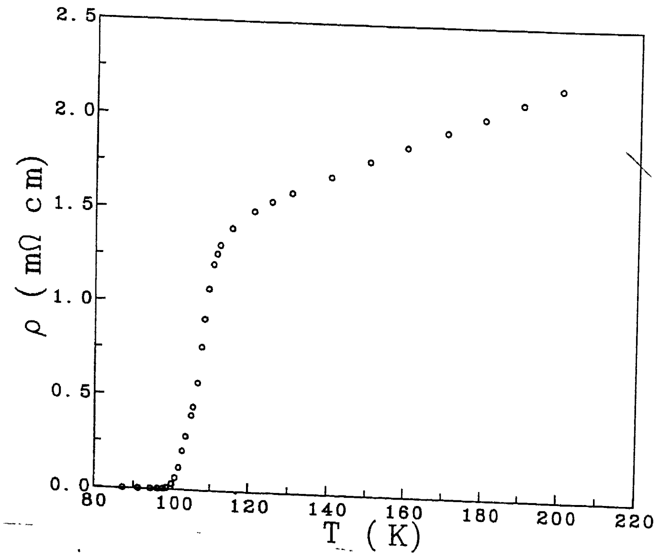


Figure 1. Resistivity (ρ) as a function of temperature (T).

in other BSCCO granular materials and is likely a result of weak intergranular coupling. The fall in ρ between 113 and 105 K is associated with the onset of superconductivity within the grains. Between 105 and 98 K the decrease in ρ is due to phase incoherence between the grains, and below 98 K phase coherence sets in. There appears a distinct change in $\rho(T)$ at 105 K corresponding to $\rho \approx 458\ \mu\Omega$ cm, i.e. $\rho(105\ \mathrm{K}) < \rho(0\mathrm{K})$ (extrapolated) $\simeq 1\cdot19$ mΩ cm. The value of $\rho \geq 458\ \mu\Omega$ cm is identified with the ρ of decoupled grains.

In figures 2–7 the variation of ρ as a function of applied dc magnetic field, H_a, for temperature $T = 81\cdot5$, 85, 90, 95, 100, and 105 K, respectively are shown. The samples are zero-field-cooled at each temperature, and then ρ is measured in the field increasing ($H^{\uparrow}$) mode and in the field decreasing ($H_{\downarrow}$) mode from a maximum field, $H_m = 38$ G. Pronounced hysteresis is observed between $H^{\uparrow}$ and $H_{\downarrow}$ at all measured temperatures. The value of magnetoresistivity $\Delta\rho(H)$ ($= \rho(H)$-$\rho(0)$) at any given field increases as the temperature is increased up to 105 K. At 110 K $\Delta\rho(H) \simeq 0$.

At $T = 81\cdot5$ (figure 2) magnetoresistance is observed beyond a field $H_1^{\uparrow} \simeq 12$ G. In $H^{\uparrow}$ mode the nature of the curve is such that the derivative $dR(H_a)/dH_a$ always increases and no discontinuity is observed. When the field is lowered from $H_m =$ 38 G, it is observed that $\rho(H_{\downarrow}) < \rho(H^{\uparrow})$. It is also found that in $H_{\downarrow}$ mode $H_{1\downarrow} \simeq 15$ G and for $H_a < 12$ G, $\rho(H_{\downarrow}) = \rho(H^{\uparrow}) = 0$. For $T = 85$ K (figure 3) the behaviour of $\rho(H)$ is similar to that at $T = 81\cdot5$ K except for $H_1^{\uparrow} = H_{1\downarrow} = 9$ G.

At $T = 90$ K (figure 4) the behaviour of $\rho(H)$ departs from the lower temperatures ones. Here $H_1^{\uparrow} = 3\cdot5$ G beyond which ρ increases rapidly and above $H_2^{\uparrow} = 20$ G the rate of rise in $\rho(H)$ decreases, i.e. $dR(H_a)/dH_a$ undergoes a discontinuity at H_2. The resistivity at H_2 corresponds to $36\ \mu\Omega$ cm. On lowering the field from H_m, $\rho(H_{\downarrow}) < \rho(H^{\uparrow})$ till H_3, below which $\rho(H_{\downarrow}) > \rho(H^{\uparrow})$. In addition $\rho(H_{\downarrow}) \neq 0$ when H_a is lowered to 0. This may be termed as the remanent magnetoresistivity analogous to remanent magnetization.

At $T = 95$ K (figure 5), $H_1^{\uparrow} \simeq 2$ G, the field $H_2^{\uparrow}$ occurs at 6 G. Above $H_2^{\uparrow}$ the rate of increase falls rapidly and field dependence appears to reach a saturation. On lowering H_a from H_m, H_3 is found to shift to higher field i.e. 7 G. For $H_a < H_3$ a minimum in $\rho(H)$ is observed for $H_a \simeq 2$ below which the resistance increases on lowering the field. The remanent resistivity increases to $46\ \mu\Omega$ cm.

For $T \geq 100$ K (figures 6 and 7), $H_1 = 0$, $H_2 = 0$, i.e. the region below $36\ \mu\Omega$ cm is absent. The resistivity rises very rapidly at small fields and appears to saturate for $H_a > 10$ G. On decreasing the field from H_m very small hysteresis is observed at 100 K. The hysteresis is nearly absent in the case of $T = 105$ K. On decreasing H_a to 0, however, remanent magnetoresistivity is observed.

There are two characteristic break points, fields H_1 and H_2. The magnetic field causes a shift in the phase difference along the tunnel barrier between the grains thereby reducing J_c. H_1 is the field at which transport current density, J', attains the critical current density, J_c' of the weak links. Therefore, the temperature dependence of field $H_1(T)$ arises from the temperature dependence of $J_c(T)$. The change in the functional dependence of $\rho(H)$ at H_2 may be for the following reasons (Gerber *et al* 1982), either (i) at H_2 almost all the Josephson junctions are suppressed and the field H_2 corresponds to effective critical field of the assembly of junctions, H_{cJ}. Therefore the field dependence of $\rho(H)$ below H_2 corresponds to that of network of Josephson junctions. Above H_2 since the weak links are absent the rate of increase in magnetoresistivity with field sharply reduces. However,

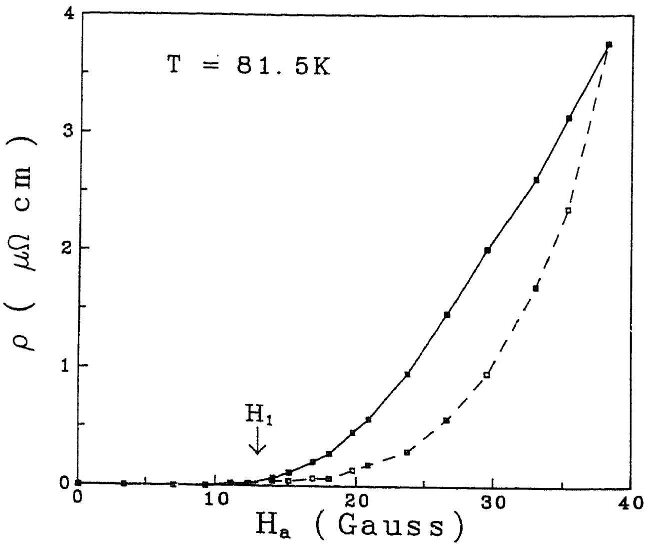


Figure 2. For caption, see p 612

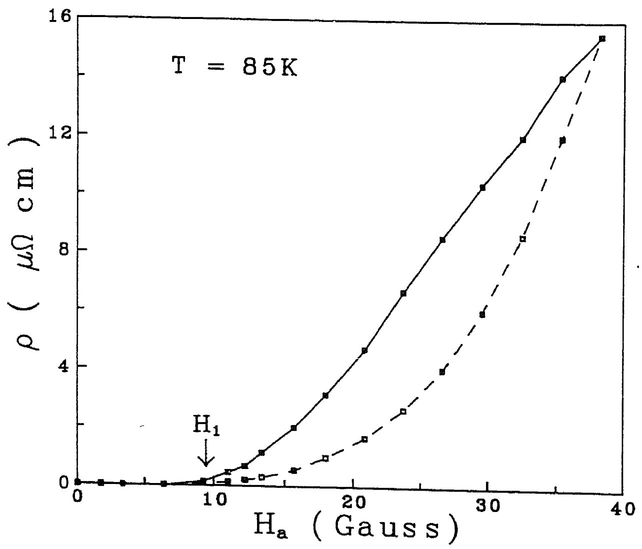


Figure 3. For caption, see p. 612.

an appropriate power law fitting of the form $\rho(H_a) \propto H_a^n$, is improper to make as in the ZFC case here as the intergranular field is not only hysteretic, but is also affected by the field compression effects, or (ii) H_2 corresponds to the field at which the $H_{\rm eff}$ $(H_2) \geq H_{c1g}$ as also suggested by Lopez *et al* (1992). The additional flux will now be distributed evenly in the volume of the sample. This would decrease the flux density in the junctions and therefore, the sample resistance will increase slowly for $H_a > H_2$.

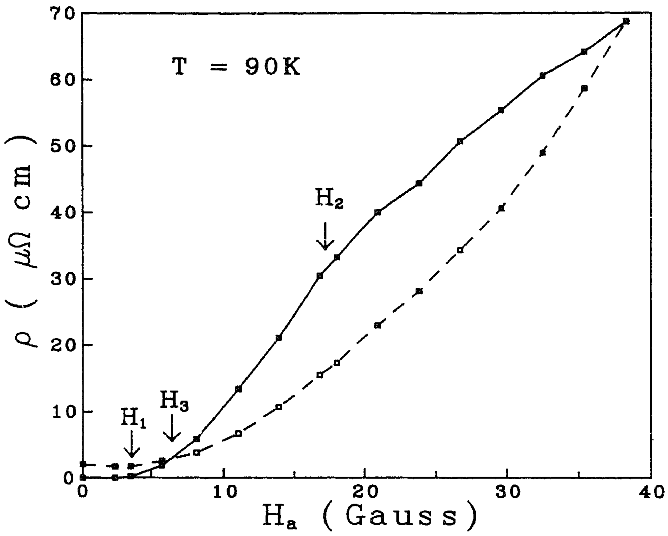


Figure 4. For caption, see p. 612.

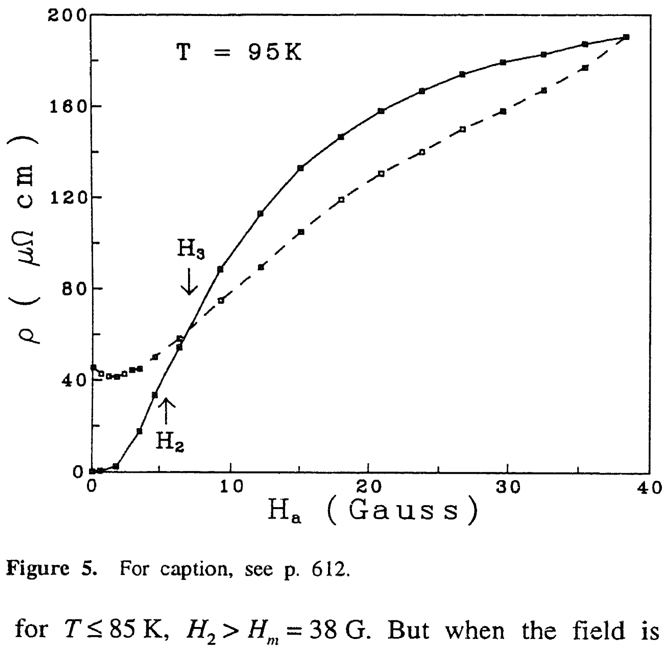


Figure 5. For caption, see p. 612.

We find for $T \leq 85$ K, $H_2 > H_m = 38$ G. But when the field is reduced from H_m hysteresis is observed. Hysteresis is a signature of H_{eff} $(H_m) > H_{c1g}$. Therefore, here $H_{c1g} < H_2$. Pradhan A K (unpublished) from second harmonic and magnetoresistance measurements shows that $H_{c1g} < H_2$. Therefore, the second possibility is incorrect. We identify H_2 with the field at which majority of the weak links are destroyed. Since the junctions have a distribution of critical fields the transition from weak link dominated ρ(H) to region where ρ(H) arises from flux creep process in the grains is not sharp. The two regions are overlapping.

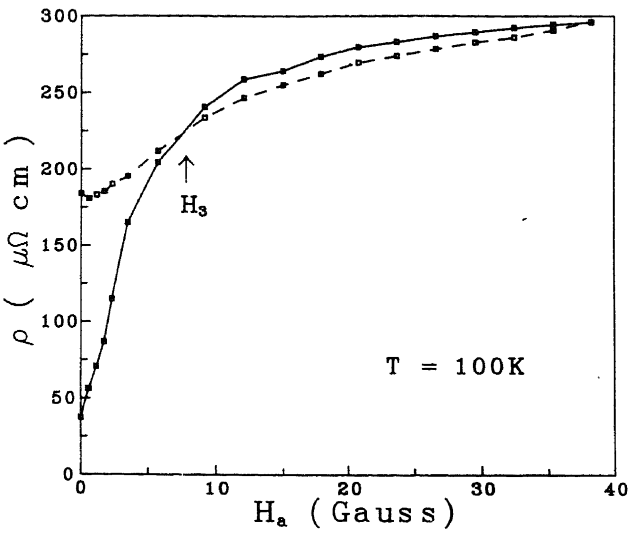
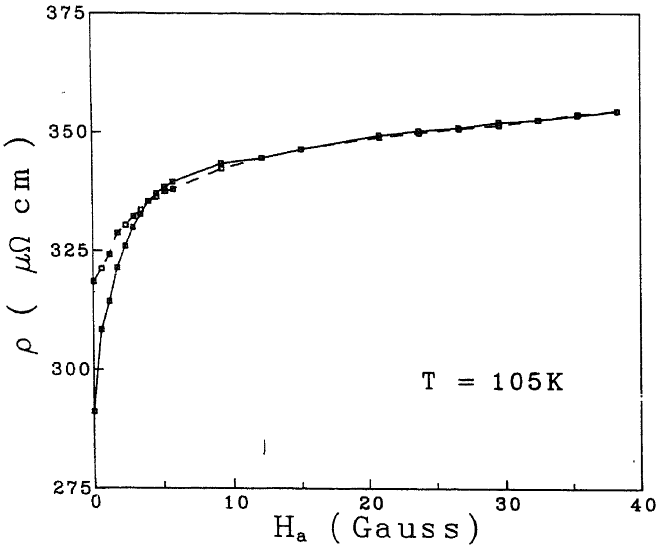


Figure 6.



Figures 2–7. Resistivity (ρ) as a function of DC magnetic field (H_a) at temperatures 81·5, 85, 90, 95, 100, 105 K, respectively. The continuous line indicates the field increasing mode ($H^{\uparrow}$) and the dashed line indicate the field decreasing mode ($H\downarrow$).

On reducing the field from H_m, $\rho(H_{\downarrow}) < \rho(H^{\uparrow})$. This is understood to be due to vectorial cancellation of H_a and the trapped field in the grains which creates a field in a direction opposite to H_a. Therefore, $H_{\rm eff}$ ($H_{\downarrow}$, ZFC) $< H_{\rm eff}$ ($H^{\uparrow}$, ZFC) (Shailendra Kumar *et al* 1992). At $T = 105$ K (figure 7) on reducing the field from H_m the hysteresis is nearly absent. This is because as T approaches T_c the pinning potential reduces and therefore less trapping in the grains occur which therefore, reduces the hysteresis. On lowering H_a further, at a field, H_{comp}, the field due to the trapped flux in the grains is exactly compensated by H_a, i.e. $H_{eff} \simeq 0$ (Das *et al* 1994). At H_{comp}, J_c exhibits a maximum (Evetts and Glowacki 1988) and even harmonics a minimum (Roy *et al* 1992; Das *et al* 1994). For $H_a < H_{comp}$, H_{eff} reverses its sign (Das *et al* 1994). Since $J_c \propto 1/|H|$ for $H_a < H_{comp}$, J_c decreases. Experimentally it has been observed by other workers that, H_{comp} increases and then saturates as H_m is increased. Furthermore, the peak of J_c broadens and its height decreases as we increase H_m. Both these observations are explained by the model of Müller and Mathews (1993) which takes into account the magnetization as well as the material parameters, viz. the grain boundary length and the probability distribution of the demagnetization factor. We have kept H_m constant and increased the temperature. At a fixed temperature raising H_m is equivalent to raising H_m relative to H_{clg}. But keeping H_m fixed, raising temperature lowers H_{clg} and therefore has the same effect. Therefore, as the temperature is raised the peak value of $J_c(H_\downarrow)$ decreases which leads to the observation of non zero remanent magnetoresistance as the temperature increases. Our observation of $H_{comp} > 0$ for BSCCO system is in contradiction with the observation of Muné *et al* (1994) who find from $J_c(H)$ measurements no evidence of H_{comp} at 77 K. The absence of H_{comp} is explained on the basis of brick wall model of Bulaevski *et al* (1992).

4. Conclusions

From the present study of $\rho(H, T)$ we find that at all temperatures between 81·5 and 105 K hysteresis exist between field increasing and decreasing modes. Existence of hysteresis is taken as an indication of $H_{eff}(H_m) \geq H_{clg}$. The field at which a discontinuity in $d\rho(H_a)/dH_a$ appears is identified with the critical field of the Josephson junction network, H_{cJ}. We also find that like in YBCO systems in these systems too $H_{comp} > 0$.

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References

Bulaevski L N, Clem J R, Glazman L I and Malezomoff A P 1992 *Phys. Rev.* **B45** 2545
Das A, Bajpai A, Banerjee A and Srinivasan R 1994 *Pramana-J. Phys.* **43** 211
Evetts J E and Glowacki B A 1988 *Cryogenics* **28** 641
Gerber A, Grenet Th, Cyrot M, and Beille J 1992 *Phys. Rev.* **B45** 5099
Levy P, Ferrari H, Bekeris V and Acha C 1993 *Physica* **C214** 111
Lopez D, de la Cruz F, Shastry P, Leyarovska N and Matacolta F C 1992 *Phys. Rev.* **B46** 11160
Müller K-H and Mathews D N 1993 *Physica* **C206** 275
Muné P, Altshuler E, Musa, J, Garner S and Riere R 1994 *Physica* **C226** 12
Peterson R L and Ekin J L 1988 *Phys. Rev.* **B37** 9848
Roy S B, Shailendra Kumar, Chaddah P, Ram Prasad and Soni N C 1992 *Physica* **C198** 383
Shailendra Kumar, Roy S B, Chaddah P, Ram Prasad and Soni N C 1992 *Physica* **C191** 450