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Title: ANISOTROPIC TRANSPORT PROPERTIES OF BSCCO SINGLE CRYSTALS AND AG_CLAD TAPES IN HIGH MAGNETIC FIELDS

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Anisotropic Transport Properties of BSCCO Single Crystals and Ag-Clad Tapes in High Magnetic fields

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Abstract

We report measurements of resistivity and critical current density on single crystals of Bi-2212 with current flow both parallel and perpendicular to the CuO_2 planes and in magnetic fields to 18T. For comparison, similar measurements were performed on samples of Bi-2223 tape conductors with the Ag cladding removed. For current flow along the c-axis of the crystals the semiconducting behavior (resistivity increasing with decreasing temperature) is extended to below 50K in a field of 18T, followed by a sharp transition to the superconducting state. From I-V curves of c-axis transport we extract the magnetic field and temperature dependencies of the interlayer critical current density $J_{c,c}$ and define a decoupling line $H_D(T)$ above which $J_{c,c}$ vanishes. $H_D(T)$ lies close to but above the irreversibility $H_{irr}(T)$ obtained from magnetic measurements. We also observe a decoupling induced below $H_D(T)$ by the application of a magnetic field starting from the zero field cooled state, ZFC. The resulting "pancake vortex" density gradient causes a loss of c-axis phase coherence and produces a c-axis resistance that relaxes logarithmically with time as the magnetization decays. These results are contrasted with similar measurements performed on highly textured Bi-2223 tapes. For current flow along the tape normal (nominal c-axis) the resistivity is metallic and its temperature and field dependence scales with those for in-plane current flow . Similarly critical currents for the two directions show similar field and orientation dependence. These results are consistent with predominant percolative current paths along crystallographic ab planes even for transport normal to the tape plane..

Introduction

The layered structure of the cuprate high temperature superconductors, HTS, gives rise to highly anisotropic physical properties. This is most evident in the Bi-2212 compound, where torque magnetometry measurements [1] indicate an anisotropy factor $\gamma = (m_c/m_{ab})^{1/2}$ greater than 150; m_c/m_{ab} is the effective mass ratio in the two directions. This implies that the coherence length ξ_c will be substantially smaller than the interlayer distance over most of the H-T phase space and that the order parameter will decay to a very small value between adjacent pairs of CuO_2 planes. This situation corresponds to the Josephson coupling of the layers and is described by the Lawrence-Doniach model [2]. In the presence of a magnetic field along the c-axis, two dimensional " pancake " vortices[3] are presumed to form in the planes that are weakly coupled to pancakes in adjacent planes by Josephson and by magnetic interactions. This general picture provides a framework for understanding the exceptionally anisotropic transport properties that have been observed in single crystals of Bi-2212. Near T_c the ratio of resistivities in the normal state $\rho_c/\rho_c \sim 10^5$ and ρ_c is an increasing function of decreasing temperature[4]. With a magnetic field along the c-axis, this semiconducting behavior in ρ_c continues to lower temperatures while ρ_{ab} is dropping rapidly below its normal state extrapolation and is described by vortex dynamics. Critical current densities, $J_{c,ab}$, for current flow along ab-planes in single crystal thin films of Bi-2212 and of Bi-2223 show scaling with the c-axis component of the magnetic field and near independence of the ab-plane component[5]. This universal dependence on the number density of pancakes in the planes is a further corroboration of the model.

One of outstanding questions remaining concerns the nature of the transition to the superconducting state along the c-axis in the presence of c-axis magnetic fields. Above the peak in ρ_c, Gray and Kim[6] have described the semiconducting behavior by assuming that the layers are decoupled in the sense that Josephson current flow is absent and conduction is provided solely by quasi-particle tunneling, which is progressively frozen out as the temperature decreases. Below the peak, the rapidly decreasing ρ_c is due to increasing conductance by Josephson currents as phase coherence along the c-axis develops. It is clear that the function of the magnetic field in depressing this transition is provided by disorder introduced by fluctuations of pancake vortices. Glazman and Koshelev [7] first pointed out that thermal fluctuations of pancake vortices suppress the superconducting long range order along the c-axis. More recently Daemen et al. [8] calculated the c-axis critical current density for a stack of Josephson-coupled layers with a magnetic field along the c-axis, treating the vortex fluctuations and anisotropy parameter self consistently and found a second order decoupling phase transition for large γ. Perfect alignment of pancakes along the c-axis allows long range phase coherence and maximizes the Josephson critical current. A pancake displaced from alignment either by thermal fluctuation or pinning generates a phase difference between adjacent layers that reduces the local critical current. At the decoupling transition the phase coherence along the c-axis is broken and $J_{c,c}$ vanishes. Recent Monte Carlo simulations [9,10] of vortex fluctuations in layered superconductors suggest a more continuous crossover characterized by the establishment of a macroscopic correlation length along the c-axis as fluctuations decrease with decreasing temperature. Dissipation generated by the interaction of c-axis currents with Josephson strings associated with pancake fluctuations may prevent a sharp transition in the c-axis resistance.

In this work we present new results on c-axis resistivity of a Bi-2212 single crystal measured in c-axis magnetic fields up to 18T. In addition we have determined $J_{c,c}(B,T)$ from I-V curves measured in the vicinity of the decoupling transition. We observe a rapid decrease of $J_{c,c}$ to immeasurably low values along a line $H_D(T)$ above which the I-V curves are ohmic and we associate this line with the decoupling transition. An as yet unresolved issue is whether $H_D(T)$ lies above or below the irreversibility line H_{irr} (T) which marks the vanishing of measurable critical currents $J_{c,ab}$ in the ab plane or alternatively with the melting of the pancake vortex lattice. Our determination of $H_{irr}(T)$ from magnetic measurements indicates that $H_{irr}(T)<H_D(T)$. This implies that, as the temperature increases, the vortex system first melts into a liquid state in which substantial c-axis correlations are maintained; and ,then, at higher temperatures all correlations of pancakes inside the planes and along the c-axis are lost. We also employ a new [11,12] experimental technique for probing interlayer coupling in which the c-axis phase correlation below $H_D(T)$ is destroyed by the application of a magnetic field starting from the zero-field-cooled, ZFC, state. The resulting pancake vortex density gradient produces disorder along the c-axis that produces a c-axis resistance that decays with time. By comparing $\rho_c(T)$ from both ZFC prepared states and from field cooled, FC, measurements we find that they merge along a line H(T) that agrees well with $H_{irr}(T)$ providing a new probe of the irreversibility transition.

A second aim of this work is to investigate the anisotropy of transport properties in highly textured Bi-2223/Ag tapes and to contrast these properties with those determined in the Bi-2212 crystals. Because of the unavailability of single crystals of Bi-2223, direct measurements of the anisotropy parameter and c-axis resistivity have not been made. However, arguments based on crystal structure, the functional form of the irreversibility line, and the dependence $J_{c,ab}$ on field angle in single crystal thin films all point to very large values of γ in Bi-2223 and an expectation for similar c-axis transport properties to those observed in Bi-2212. In highly textured polycrystalline tape materials large current densities must be transferred across grain boundaries and the nature of the mechanisms that limit critical currents at elevated fields and temperatures is very important to understand. The popular "brickwall" model [13] envisions current transfer across large area c-axis twist boundaries in these plate-like microstructures and would require substantial current transport along crystallographic c-axes. This c-axis transport should be dominant for current flow normal to the tape plane and should show properties inherent to Josephson coupled layers described above. We have made a detailed study of resistivity and critical currents parallel and normal to Bi-2223/Ag tape planes in order to determine the dominant current paths [14]. We find no evidence for limitation by c-axis current transport. These results will be discussed in terms of their implications for the percolative nature of current flow in these materials..

Experimental

Two single crystals of Bi-2212 were studied with dimensions of 0.925x0.45 x 0.0089mm^3 for c-axis currents and 1x0.28x0.0076mm^3 for in-plane currents, with T_c~ 85K and ~87K respectively. The contacts were made using silver paste by curing 12h in air at 500-600^{o}C and then quenching to room temperature. The current contacts covered most of the two crystal ab-plane faces for a uniform c-axis current density; and, for the in-plane currents , the current contacts covered the sides of the crystal to ensure the absence of a c-axis component and current uniformity. The measurements were done with a standard 4-contact method using both ac and dc currents. For ρ_c in high magnetic field , the excitation current for the ac bridge was 30μA. The resistivity was independent of currents up to 1mA in either orientation. The high magnetic field measurements were taken in an Oxford 20T superconducting magnet at the National High Magnetic Field Laboratory at Los Alamos National Laboratory. The critical current density along the c-axis, $J_{c,c}$, with B $\parallel$ c was determined from I-V curves with a 1nV criterion.

To measure anisotropic properties of Bi-2223 tapes, we used the core of a piece of tape from which the Ag sheath had been mechanically removed for ρ_r resistivity along the rolling plane(close to the crystallographic ab plane). For ρ_n (resistivity parallel to the tape normal) and critical current measurements for this orientation, we removed the Ag sheath from the sides of the tape and applied current and voltage contacts to the intact top and bottom Ag surfaces , ensuring good ohmic contact and uniform current flow.

Bi-2212 Single Crystal Results

In figure 1 we show the results for ρ_c versus T for a Bi-2212 crystal in magnetic fields along the c-axis of 0.1-18T. As previously observed at lower fields [4], ρ_c continues to rise with decreasing temperature until a peak is reached at a temperature Tp that falls with increasing field. Tp is observed to decrease more rapidly as a function of B at low B. Above Tp no c-axis magnetoresistance is observed in this field range and the temperature dependence can be described approximately by ρ_c~exp(200/T). Gray and Kim [8] modeled this behavior as arising from quasi-particle tunneling between decoupled superconducting layers. In this same region ρ_{ab}(T) (not shown here) is dropping rapidly below its normal state extrapolation. Below T_p, ρ_c drops rapidly as interlayer coupling develops and c-axis supercurrents begin to flow. The slope of ρ_c versus T below Tp becomes sharper with increasing field in contrast to the behavior of ρ_{ab}, where, at low temperatures, higher magnetic fields broaden the transition.

In order to study the nature of this transition in ρ_c we next present results from I-V curves taken at temperatures near where ρ_c reaches zero. Typical results are shown in Fig.2a for different temperatures at H=4T (the I-V characteristics for different fields are similar). At low temperatures T< 30K, the voltage remains very low with current density up to ~14.5 A/cm^2; then there is a jump to a resistive state. The magnitude of this jump increases with magnetic field. A non-vanishing critical current is observed in this low temperature range for the field range 0-7T covered in these measurements. At temperatures above 30K the I-V curves are ohmic at low currents as shown in the inset of Fig.2a .

In Fig.2b we plot $J_{c,c}$ (1nV criterion) versus T at various fields. As shown ,there exists an abrupt decrease of $J_{c,c}$ with respect to temperature and magnetic field. At low temperatures the critical current is strongly suppressed by magnetic fields, but then appears to saturate above 4T. The critical current also exhibits a reentrant behavior with respect to temperature at high magnetic fields. A similar effect was previously reported by Rodriguez et al.[11] for $J_{c,c}$ measured after fields were applied starting from the zero-field-cooled, ZFC, state. By contrast our results were obtained from a field-cooled, FC, condition. Based on the data presented in Fig.2b, we define $H_D(T)$ as the field(temperature) above which $J_{c,c}$ becomes zero (with our criterion ~1nV). Extrapolations of the data in Fig. 2b to $J_{c,c}=0$ introduce a maximum error of 2K, the interval of the data, and is reflected in the error bars shown in Fig.3 . The decoupling line $H_D(T)$ is shown in Fig. 3 with the irreversibility line obtained by Schilling et al.[15], as well as one obtained on our crystal from magnetic measurements. We see that these lines follow a similar functional dependence with $H_D(T)$ lying ~ 5K above the irreversibility lines $H_{irr}(T)$. The relation between depinning in the ab plane and decoupling along the c-axis will be discussed below.

Following the idea [8], discussed in the introduction ,that decoupling is associated with disorder along the c-axis in pancake vortex positions, we now present results that show the effect of pinning induced disorder on $J_{c,c}$. Application of a c-axis aligned magnetic field at low temperatures from the ZFC state produces a pancake vortex density gradient in the ab planes that begins from near a critical state after the field is stabilized and then relaxes by thermally activated flux motion. The strong Lorentz force associated with the gradient and compensated by the random array of pinning forces from defects is expected to disrupt spatial correlation of pancakes along the c-axis. This is illustrated by the 3 panels in Fig.4 . In the lower 2 panels the c-axis current is below $J_{c,c}$ for the FC state for 2T at low temperature. It is seen that the application of a field from the ZFC state decouples the layers and produces a resistive state along the c-axis. This resistance is seen to decrease with increasing temperature, which we attribute to the relaxation of the ab plane flux profile with increasing temperature leading, to a more ordered state along the c-axis. In the upper panel the current density is above $J_{c,c}$(FC) and the FC resistance is seen to rise with temperature illustrating the effect of thermal fluctuations on decoupling. The point of mergence of the FC and ZFC data marks the temperature where a vortex gradient sufficient to affect R_c can no longer be sustained in the ab plane and is equivalent to an irreversibility point. An irreversibility line determined in this manner is plotted in Fig.4 as $R_{c,irr}$. This line is seen to agree well with the H_{irr}(T) lines from magnetic measurements. A further corroboration of the association of R_c(ZFC) with the ab plane flux gradient is shown in Fig. 5 . Here we have plotted normalized values of R_c and the magnetization M_c as functions of time. It is seen that R_c decays with time approximately logarithmically and follows very closely the magnetic relaxation that proceeds by flux motion in the ab plane. Similar results have been recently reported from ZFC studies of c-axis I-V curves on Bi-2212 single crystals by Rodriguez et al.[11] and by de la Cruz et al. [12].

Discussion

The ρ_c(T) results shown in Fig.1 illustrate the effect of a c-axis magnetic field in suppressing the flow of supercurrents between the planes. At 18T T_P is depressed to below 50K. In the recent Monte Carlo simulation by Hellerquist et al.[10], T_P marks the temperature below which vortex fluctuation amplitudes have decreased to a level that allows a finite phase correlation length to develop permitting conductance by Josephson currents. The development of a finite critical current density $J_{c,c}$ along the c-axis also requires the absence of thermally activated dissipation and may therefore be linked to the irreversibility/melting transition of the pancake vortices in the ab plane. The low temperature I-V curves.presented in Fig. 2 , show that $J_{c,c}$ is also strongly suppressed at high magnetic fields at low temperatures. Bulaevskii[16] has recently shown that this may be explained as due to disruption of pancake alignment by strong pinning. The increasing density of disordered pancakes with field then leads to a loss of phase coherence along the c-axis. This also provides an explanation for the reentrant behavior in $J_{c,c}$ seen in Fig.2b , since increasing temperature leads to thermal depinning and initially to improving alignment. This effect is countered by the increase of fluctuation amplitudes which eventually results in a greater loss of coherence. as $H_D(T)$ is approached. The effect of static disorder is seen directly in the ZFC experiments where the presence of vortex gradients and the associated Lorentz force in the ab plane is coupled to a loss of pancake alignment in the c-direction. The logarithmic decay of R_c matching that of the magnetization shows that this decoupling is related to the flux gradient and not to its time derivative that describes flux motion velocity. Our decoupling line $H_D(T)$, from I-V curve determination of the vanishing of $J_{c,c}$, lies above $H_{irr}(T)$, in contrast to recent results from ac susceptibility measurements[12,17] that appear to show the opposite. It is not clear from the present measurements that a finite resistance is not present below the sharp transition in the I-V curve that defines $J_{c,c}$, and a true zero resistance state may not be reached until $H_{irr}(T)$, but it seems unlikely that $H_D(T)$ lies below. Our result agrees with the results of Monte Carlo simulations by Ryu et al.[9], which sees a low temperature 2D melting transition of the Berezinski-Kosterlitz-Thouless dislocation mediated class , which maintains phase correlation along the c-axis. This is followed at higher temperature by a true melting transition in which correlations are lost in all directions. Further investigations on this point are clearly called for.

Bi-2223 Tape Results

The prominent anisotropy of transport properties observed in single crystals of Bi-based HTS are expected to play a role in current transport in highly textured polycrystalline materials. In particular, current flow normal to the tape plane (along the nominal c-axis) should show the same semiconducting $\rho(T)$ seen in Fig. 1 and similar decoupling behavior in high magnetic fields in the limit of perfect texturing. In Fig.6 we show results for ρ_n (along tape normal) and ρ_r (along tape rolling plane) for 5 different Bi-

2223/Ag tapes, where the critical currents range from ~15A to ~ 31A(J_c~1.2- 2.4x10^4 A/cm^2) at 75K in self field. The striking result shown here is that ρ_n (T) is metallic in character with no sign of the semiconducting behavior seen in Fig.1. In addition , the ratio ρ_n/ρ_r at 300K is 4-10 in contrast to the single crystal values for ρ_c/ρ_{ab} which are typically 10^4- 10^5. An interesting inverse correlation shown here is that between ρ_r and I_c: the lower the in-plane resistivity, the higher the zero-field I_c.

Figure 7a shows the typical magnetic field dependence of the normalized in-plane resistivity ρ_r/ρ_r(H,140K), up to 7T for tape 1BW (I_c of ~31A at 75K). As shown, for H ∥ n, the resistivity shows much stronger dissipation than for H ∥ r . In addition Fig. 7b shows that the magnetic field dependence of ρ_n is very similar to that of ρ_r, and that the normalized resistivity scales with that of ρ_r at the same magnetic field. These behaviors indicate that the dissipation of ρ_r and ρ_n result from the same physical origin, namely, the dissipation of the currents flowing along CuO_2 planes. Also, as shown in the inset to Fig. 7a, the resistivity for H ∥ n at 1T is almost identical with that for H ∥ r at 7T. For the highly anisotropic Bi-2223/Ag tape system there has been much experimental evidence that the dissipation is primarily a function of the field component normal to the CuO_2 planes, i.e., H ∥ n .Therefore, we argue that ρ_r for H ∥ r results primarily from a misorientation of the CuO_2 planes relative to the rolling plane. From the scaling of the resistivity shown in Fig. 7a , we can deduce the average misalignment angle of this tape, tan ϕ_c= 1/7, i.e., ϕ_c= 8^o.

Figure 8 shows $I_c(\theta)$ in magnetic fields 0.1, 0.25, and 0.5T at 75K, and in 0.25, 0.5 and 0.9T at 64K for the current direction along the rolling plane (I ∥ r) and for current along the tape normal (I ∥ n). The voltage criterion is ~1μV/cm for I ∥ r and ~ 100μV/cm for I ∥ n if we use the nominal thickness of the tape ~50μm. However, the actual criteria may be smaller if the actual current path is tortuous in nature and therefore longer than the tape thickness. An important feature of the data is that the angular dependencies of the critical currents for both directions are quite similar. The scaling of the critical current as a function of the angle θ with the normal component of the field is quite good but there is a deviation for θ near 90^o. The deviations for scaling near parallel alignment for both current directions are similar. These results confirm a model of current paths primarily along tilted ab planes for $I \parallel n$. Irrespective of the value of I_c of the tape, we observed similar results for 5 different tapes. Since the critical current for $I \parallel n$ is too large to be accounted for by the Josephson-current limited transport as shown by Hensel et al.[18], the transport supercurrent does not reflect this c-axis transport and intergrain transfer mechanism. In addition, from the scaling of the magnetic field dependence of the critical currents for $I \parallel r$ and $I \parallel n$, we obtained a similar order of misalignment of $\sim 9^o$ for this tape. From these and other measurements [14], we deduce the following: (1) the resistivity anisotropy is of order 10, much reduced from the values$\sim 10^5$ observed in single crystal Bi-2212; (2) the supercurrent path for current along the rolling plane and perpendicular to it is similar and primarily along inclined crystallographic ab planes.

Summary

We have presented results of measurements of resistivity and critical currents as functions of magnetic field, field angle and current direction for single crystals of Bi-2212 and for Bi-2223/ Ag tapes. The single crystal resistivity along the c-axis shows properties of Josephson-coupled-layer superconductivity. With high magnetic field along the c-axis the transition to a superconducting state along the c-axis is suppressed, with transport being provided by quasi-particle tunneling. Coupling between layers develops as vortex fluctuations diminish with decreasing temperatures. We infer a decoupling line $H_D(T)$ from critical current measurements along the c-axis defined by the condition $J_{c,c}=0$ obtained by extrapolation. Our result that $H_D(T)>H_{irr}(T)$ is in disagreement with recent results from ac susceptibility measurements[17]. We also have reported results on decoupling produced at low temperatures by application of a c-axis field from the zero-field-cooled state,ZFC, and shown that the c-axis resistivity R_c decays with time in unison with the magnetization produced by the vortex gradient in the ab plane.The merging of R_c(ZFC) and R_c(FC) provides a new measure of $H_{irr}(T)$. None of this distinctive anisotropic transport behavior is seen in the Bi-2223/Ag tape data. It appears that the field and temperature dependence of resistivity and critical current are governed by transport along CuO_2 planes regardless of the nominal current flow direction.

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Figures

FIG. 1. The c-axis resistivity of a single crystal of Bi-2212 in different magnetic fields applied along the c-axis.

FIG. 2. (a) C-axis I-V characteristics at B=4T. Those above 30K are shown by thin solid lines, in 5K intervals from top to bottom at the right side. I-V characteristics below 30K are shown by thick solid lines. O 6K, 10K, 14K, × 18K, + 22K, Δ 26K. Inset shows the I-V curves on logarithmic scale at 30K and at various magnetic fields. (b) Critical current density, $J_{c,c}$ versus temperature at different fields as inferred from I-V curves.

FIG.3 The decoupling line $H_D(T)$ determined as described in text and irreversibility lines measured magnetically and by the merging of c-axis resistivity from field-cooled and from zero-field-cooled states.

FIG.4 C-axis resistivity versus temperature at a c-axis field of 2T at three different c-axis currents. The measurements were taken under conditions of: field-cooled-cooling, FCC; field-cooled-warming,FCW: and zero-field-cooled,ZFC.

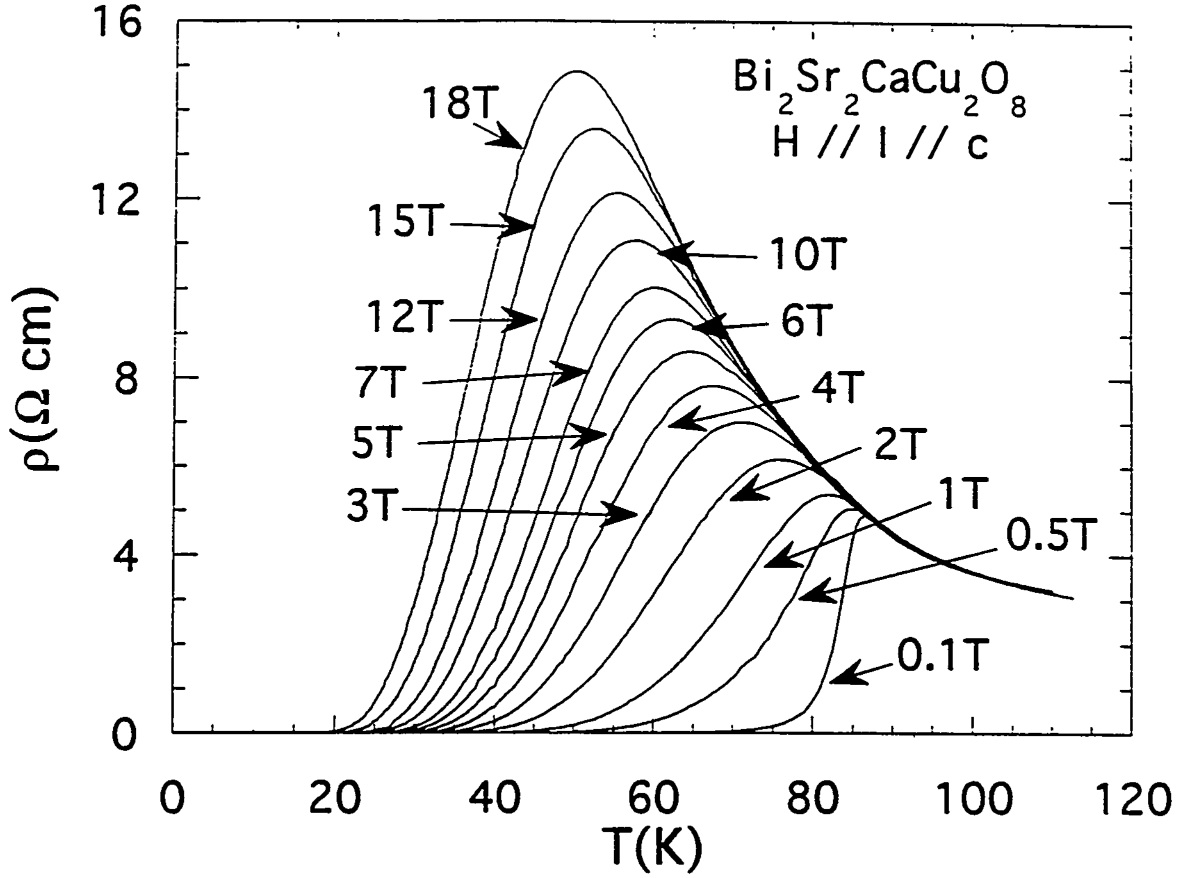
FIG. 5. Normalized c-axis Magnetization, M, (squares) and Resistance, R_c(circles) versus time after the application of a 5T field from the ZFC state. The data is normalized to values taken ~ 100s after the stabilization of the field.

FIG. 6. Resistivity, ρ_n for the current direction parallel to the tape normal and resistivity ρ_r for current along the rolling plane for five different tapes. The critical currents at 75K in self field for tapes 1BW, 2BW, 3BW, 4BW and 5BW are 31A, 27A, 17A, 15A, and 23A respectively. The inset defines the directions r and n used in the text.

FIG. 7. (a) Magnetic field dependence of the normalized resistivity versus temperature. Symbols represent ρ for $H \parallel n$ and lines for $H \parallel r$. From left to right, the magnetic fields are 7, 6, 5, 4, 3, 2, 1 and 0.5 T for each set. The inset (axes same as the main figure)

shows the scaling of ρ for one value of H ‖ r. (b) Normalized resistivity versus temperature for H ‖ n at 3T for I ‖ n and I ‖r.

FIG.8 (a) The scaling of the angular dependence of the critical current for the current along the rolling plane and normal to H, where the magnetic field H cosθ is the normal component of the magnetic field.The inset shows $I_c(\theta)$ where $\theta=90^o$ is parallel to the rolling direction r . The solid symbols at 64K are: circle 0.25T, square 0.5T, and diamond 0.9T. The open symbols at 75K are: circle 0.1T, square 0.25T, and diamond 0.5T. (b) The scaling of $I_c(\theta)$ for I parallel to the tape normal with symbols the same as in (a). H lies in the n-t plane. The inset shows $I_c(\theta)$.



16
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8
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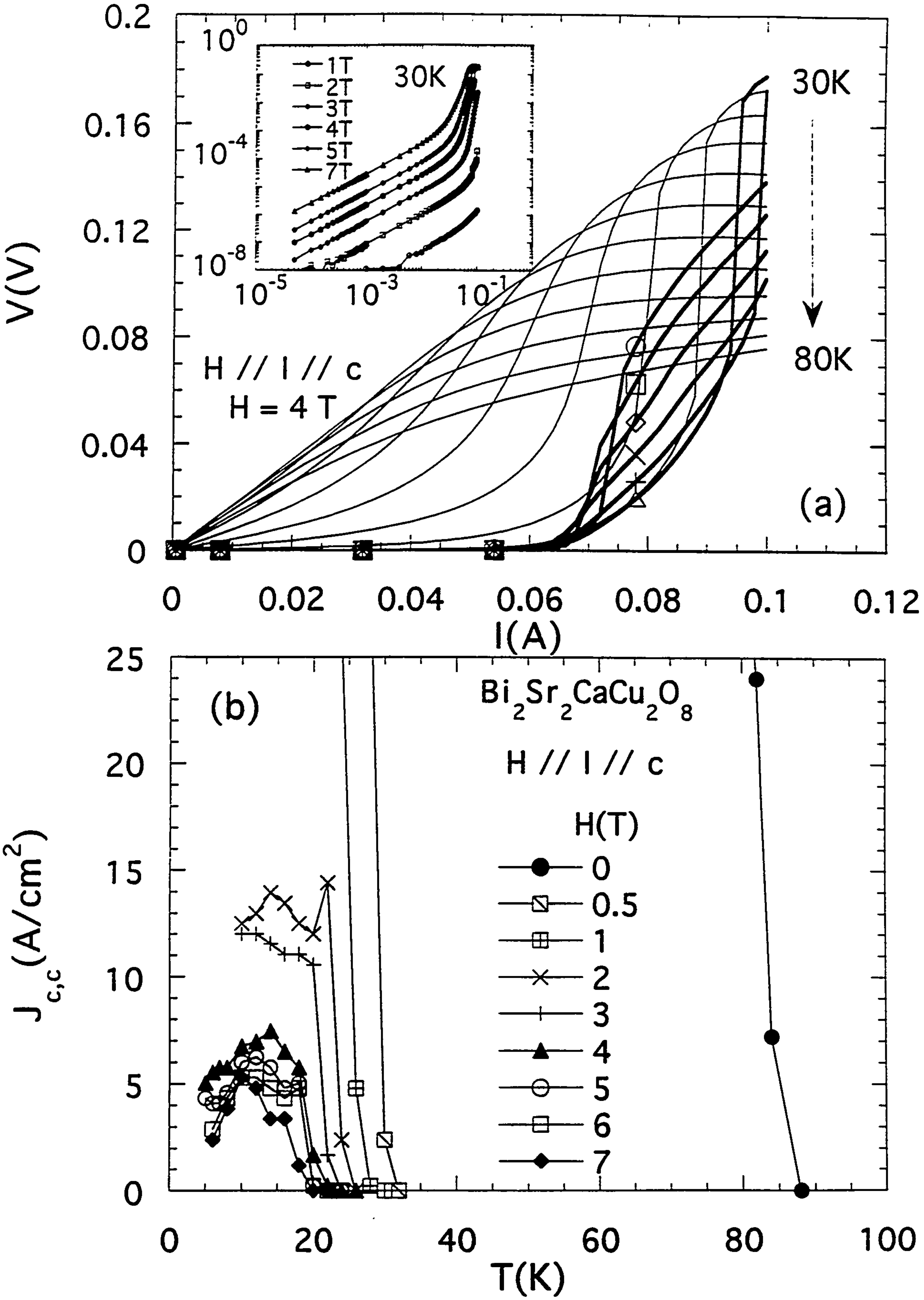
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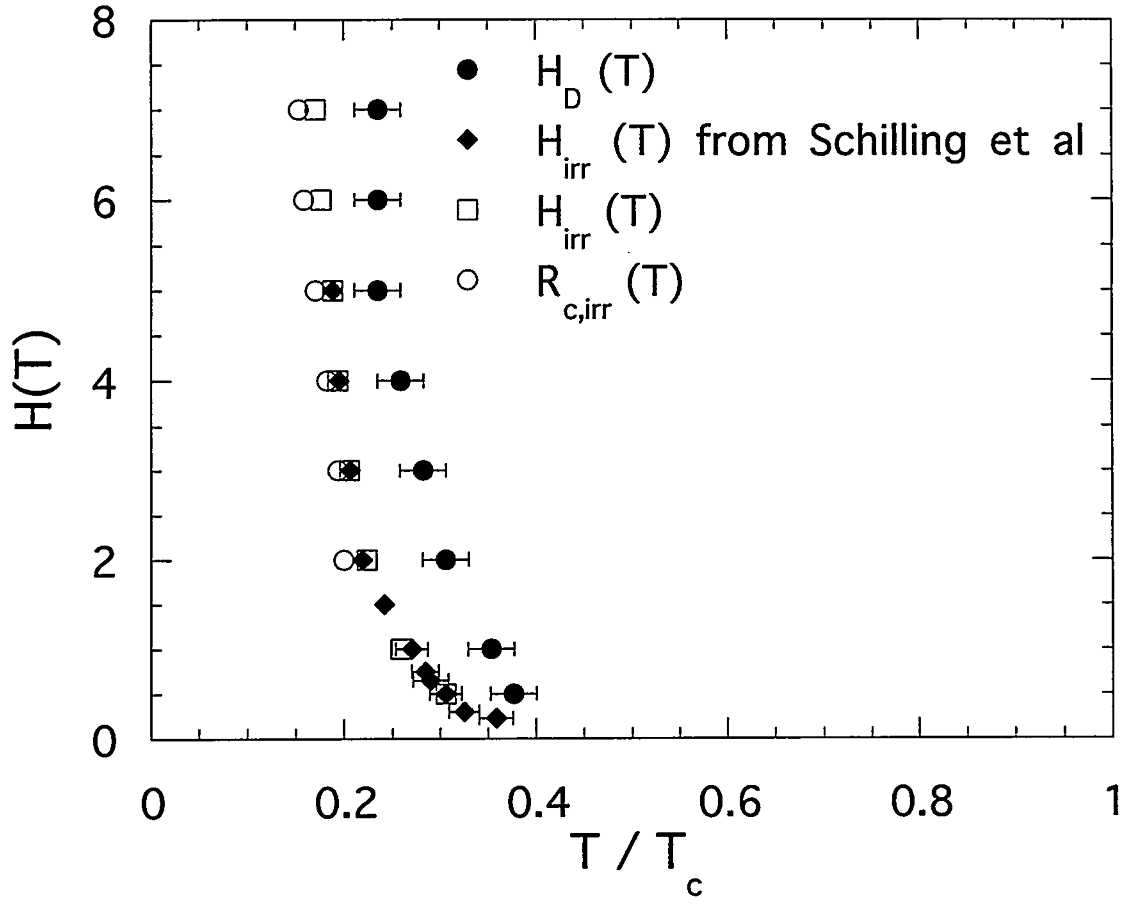
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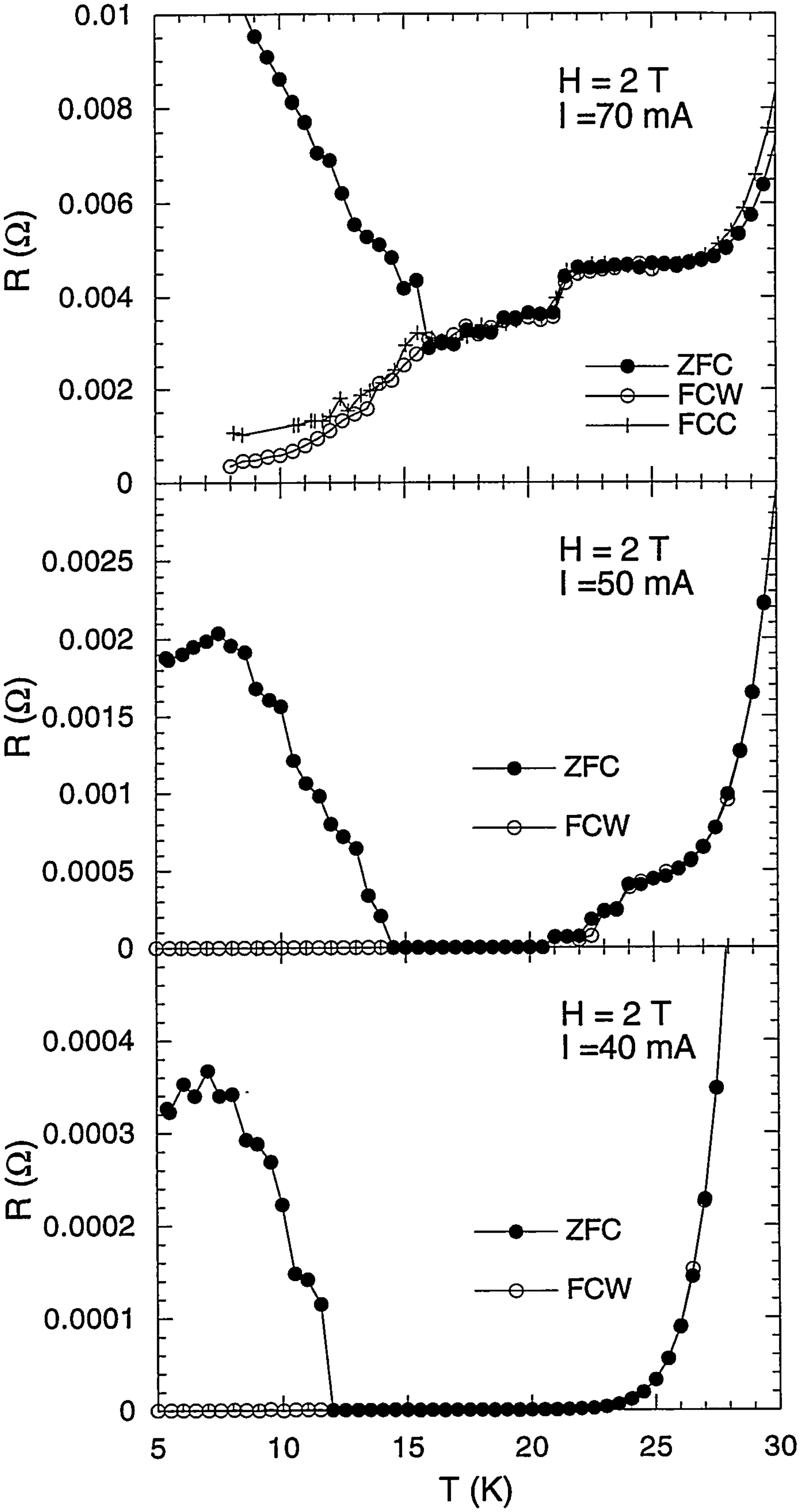
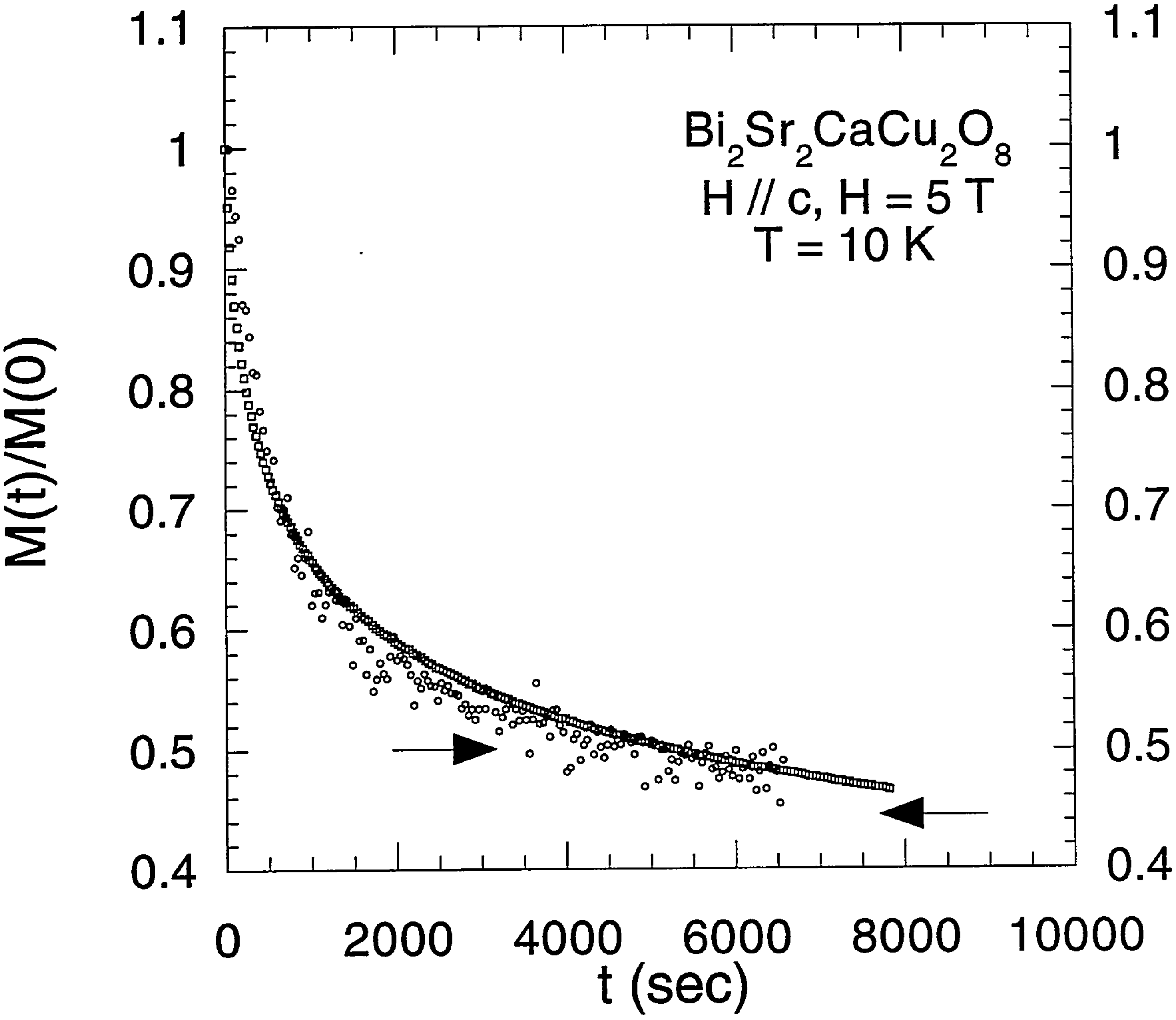
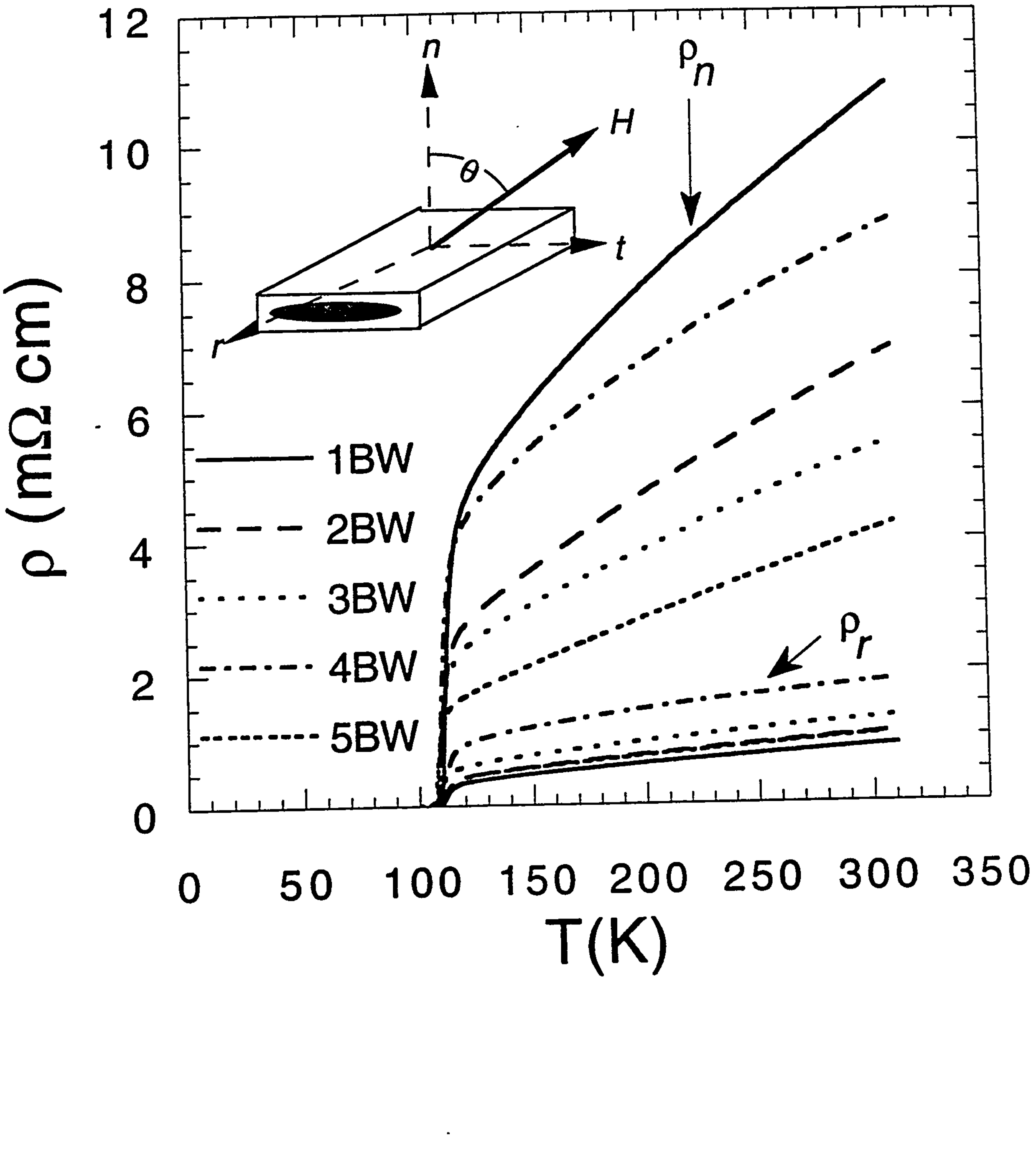
● H$_D$ (T)
◆ H$_{irr}$ (T) from Schilling et al
☐ H$_{irr}$ (T)
○ R$_{c,irr}$ (T)

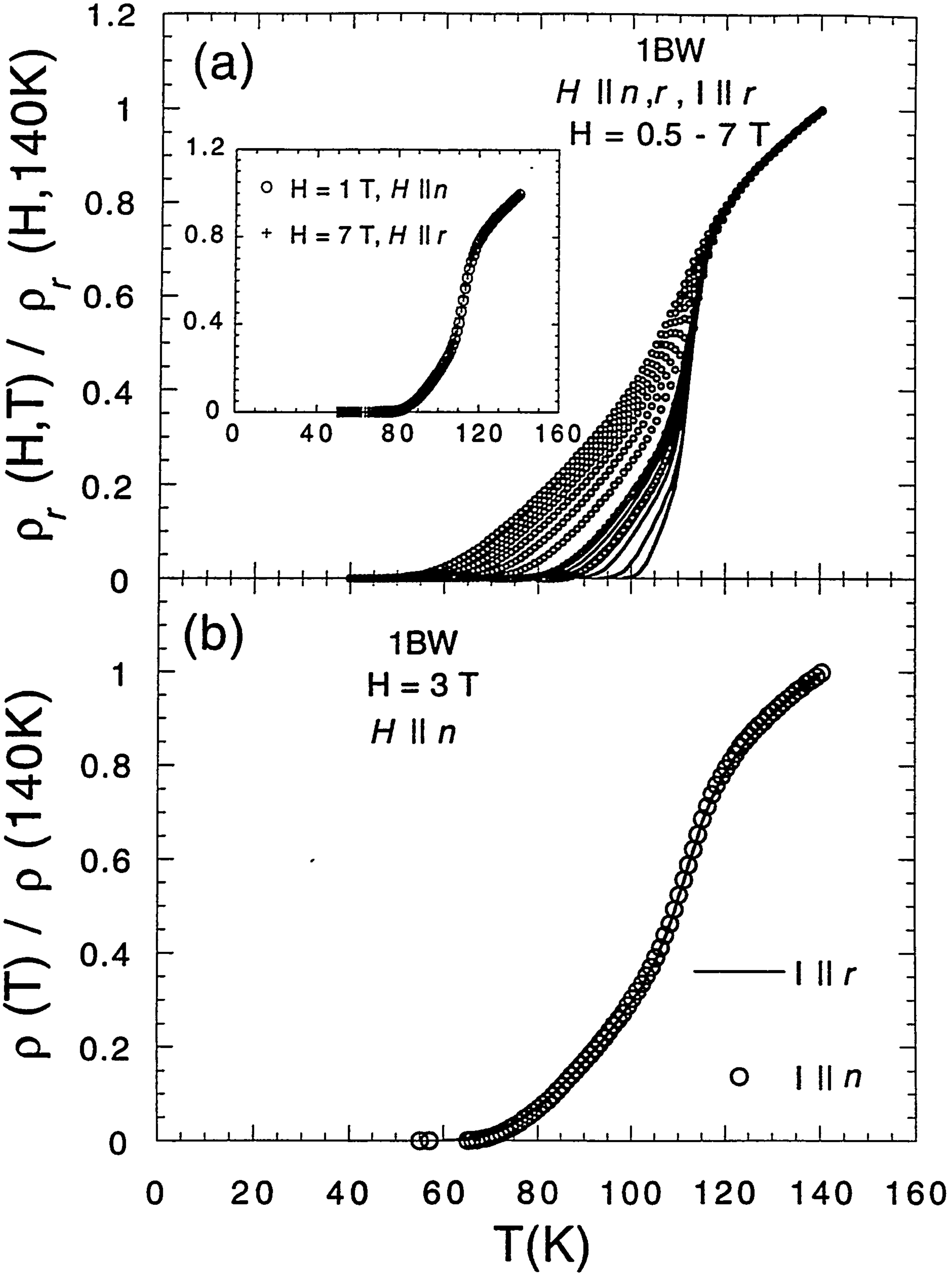


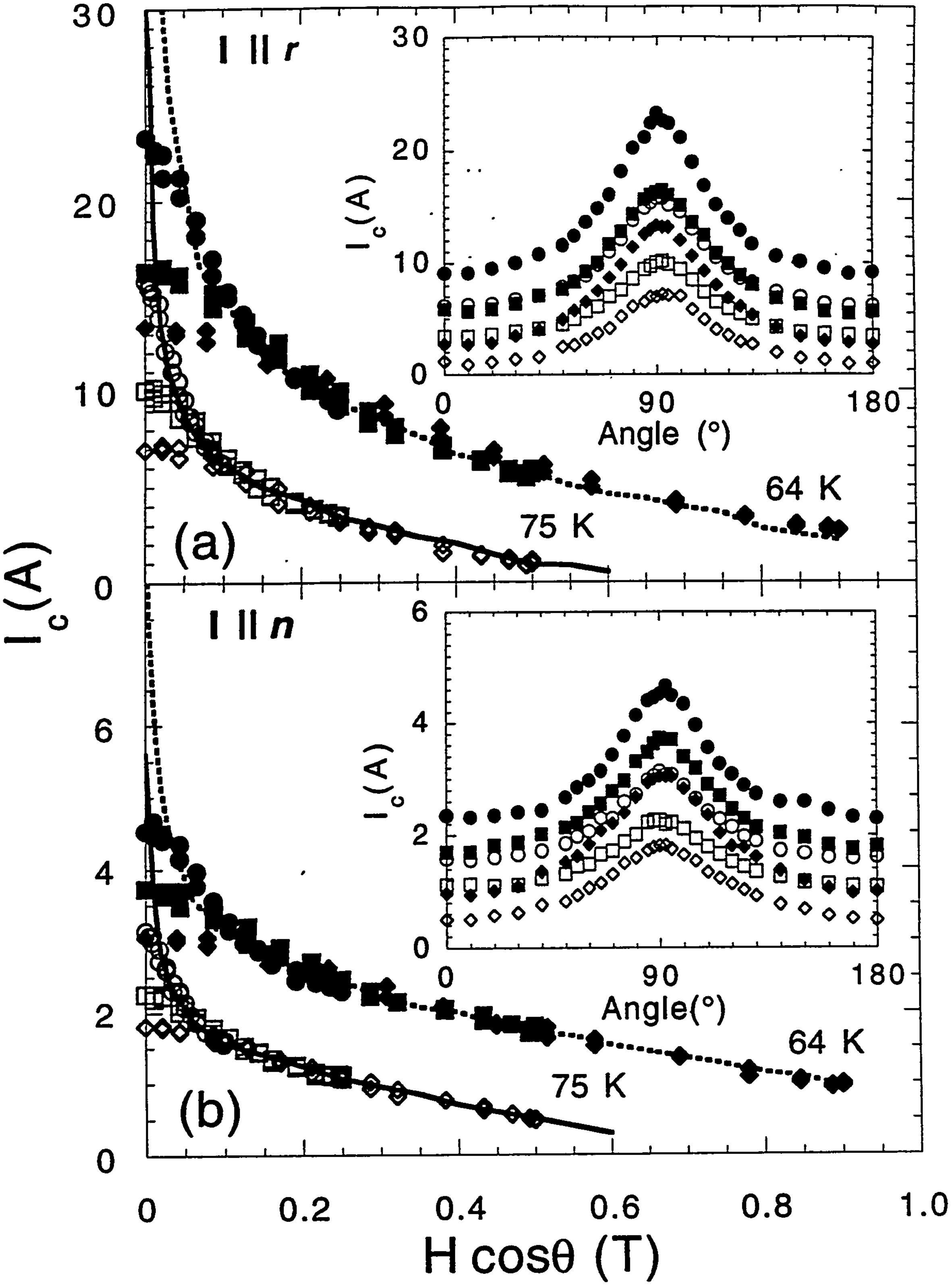
0.01
0.008
0.006
0.004
0.002
0
R (Ω)
H = 2 T
I =70 mA
ZFC
FCW
FCC
0.0025
0.002
0.0015
0.001
0.0005
0
R (Ω)
H = 2 T
I =50 mA
ZFC
FCW
0.0004
0.0003
0.0002
0.0001
0
R (Ω)
H = 2 T
I =40 mA
ZFC
FCW
5
10
15
20
25
30
T (K)


Bi$_2$Sr$_2$CaCu$_2$O$_8$
H // c, H = 5 T
T = 10 K
M(t)/M(0)
$R_c(t)/R_c(0)$
t (sec)
0
2000
4000
6000
8000
10000
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1



12
10
8
6
4
2
0
ρ (mΩ cm)
0
50
100
150
200
250
300
350
T(K)
n
H
θ
t
r
ρ_n
ρ_r
1BW
2BW
3BW
4BW
5BW


(a)
1BW
H || n,r , I || r
H = 0.5 - 7 T
H = 1 T, H || n
H = 7 T, H || r
1.2
0.8
0.4
0
0
40
80
120
160
ρ_r (H,T) / ρ_r (H,140K)
1.2
1
0.8
0.6
0.4
0.2
0
(b)
1BW
H = 3 T
H || n
I || r
I || n
ρ (T) / ρ (140K)
1
0.8
0.6
0.4
0.2
0
0
20
40
60
80
100
120
140
160
T(K)


I || r
I || n
(a)
(b)
75 K
64 K
75 K
64 K
I_c(A)
H cosθ (T)
0
0.2
0.4
0.6
0.8
1.0
0
10
20
30
0
2
4
6
I_c(A)
Angle (°)
0
90
180
0
10
20
30
I_c(A)
Angle(°)
0
90
180
0
2
4
6