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SUPERCONDUCTING TRANSITIONS AND VORTEX DYNAMICS OF 

$\text{Bi}_2\text{Sr}_2\text{Ca}_1\text{Cu}_2\text{O}_{8+\delta}$

DISSERTATION

Presentation in Partial Fulfillment of the Requirement for the Degree Doctor of Philosophy in the Graduate School of the Ohio State University by Yue-Min Wan, B.S., M.S.

The Ohio State University

1995

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Advisor

Department of Physics
To My Parents

And to the Memory of My Father . . .
ACKNOWLEDGEMENT

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PUBLICATIONS


2 "Effects of the C-axis Resistive Transition Width on the Secondary Voltage of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$", Y.M. Wan, S.E. Hebboul, D.C. Harris, and J.C. Garland, Physica B 194-196, 1515(1994).

3 Comment on "Fluxon Transition in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$", Y.M. Wan, S.E. Hebboul, and J.C. Garland, Phys. Rev. Lett. 72, 1570(1994).

4 "Vortex Phase Diagram of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ Near the Superconducting Transition", Y.M. Wan, S.E. Hebboul, and J.C. Garland, Phys. Rev. Lett. 72, 3867(1994).
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1.1 Introduction

The high resistive anisotropy in the normal state of the high temperature superconductor $\text{Br}_2\text{Sr}_2\text{Ca}_1\text{Cu}_2\text{O}_{8+\delta}(\text{BSCCO})$ highlights the importance of understanding the transition and vortex dynamics in the superconducting state. It is known that the CuO bilayers exhibit a Kosterlitz-Thouless (KT) type transition [1]. It is, however, not clear whether these layered superconductors achieve a zero-resistivity state at the KT transition, because of the non-zero out-of-plane Josephson interaction. We will begin by addressing this issue through a series of current-voltage measurements near the transition temperature in zero external magnetic fields.

The spontaneous creation of thermal vortex lines has recently been proposed by Bulaevskii, Ledvij and Kogan (BLK) [2] who assumed that BSCCO is made of Josephson-coupled two-dimensional (2D) superconductors. Besides the supporting evidence from magnetization measurements, this model remained to be tested otherwise. Here, we examine the theory of thermal vortex lines by
employing a six-contact transport method. In this "dc-flux transformer" configuration, we measure the "secondary" voltage on the bottom ab-plane, while a constant bias current is injected into the top or "primary" layer.

Another important issue about vortex dynamics, which has attracted a lot of attention, is that the Abrikosov vortex lattice in BSCCO has been found to melt when the vortex thermal motion distance becomes comparable to the vortex lattice spacing. Most recently, Brawner et al. [3] have speculated about the nature of the vortex phase diagram near the superconducting transition. Here, we use the dc-flux transformer technique to measure both the primary and the secondary voltages as a function of external magnetic field applied along the c-axis. To allow the readers to better understand the issues involved, a brief summary of previous work is given below along with the relevant theoretical models.

1.2 Review of previous studies on BSCCO

The electrical transport nature of BSCCO is generally characterized by a resistivity tensor. Martin et al. [4] have shown that the resistivity along the a and b axes are similar, with a ratio $\rho_a / \rho_b \sim 1.7$ at 100K. By contrast, a substantially larger resistivity was recorded along the c-axis, with $\rho_c / \rho_b \sim 10^5 - 10^6$. As a result, they suggested that only two resistivity components are necessary, i.e., $\rho_{ab} = (\rho_a \rho_b)^{1/2}$ and $\rho_c$, because of the nearly equal a and b axis resistivity. It is common now to use the anisotropy ratio $\Gamma = \rho_c / \rho_{ab}$. 
The temperature dependence of resistivity along the ab-plane reveals a metallic nature (linear in T) in the normal state, while the dependence shows semi-metallic behavior along the c-axis, close to T^1. The origin of the T^1 dependence was a highly controversial subject during early years. One interpretation was that the T^1 behavior reflects the intrinsic nature of quasiparticle tunneling for electrons between CuO bilayers, as proposed by Anderson et al. [6] and Anderson and Zou [7]. Another interpretation, however, attributed the effect to extrinsic topological defects acting as local short circuits throughout the crystals, as suspected by Martin et al. Currently, the favored picture is of quasiparticle tunneling along the c-axis because of the highly uniform BiO and SrO layers which provide effective insulation between successive CuO bilayers.

In the superconducting state where resistivity is zero, the anisotropy is defined as the ratio of Josephson (critical) current J or magnetic penetration depth \( \lambda \) on the c-axis and ab-plane. Martin et al. [5] have obtained a Josephson current anisotropy \( J_c/J_{ab} \sim 10^3 \) at temperatures near \( T_c \). Similarly, Farrell et al. [8] and Martinez et al. [9] found that the magnetic anisotropy ratio \( \gamma = \lambda_c/\lambda_{ab} \) is larger than 150 at 77K. This value was obtained by measuring the magnetically induced torque for small angle ( < 0.5°) misalignments between the ab-plane and external fields. Using a analogous method but a somewhat larger misalignment angle ( 6° ), Nakamura, Gu and Koshizuka [10] obtained \( \gamma \sim 700 \) at 20K. The value was also confirmed by Cooper, Forro and Keszei [11] who measured the ab-
plane and c-axis penetration depth at all temperatures from $T_c$ to 10K.

The high anisotropy leads to many researchers to believe that two dimensionality should manifest itself on the ab-plane. Mun et al. [12] found excess conductivity in the ab-plane as temperature approached $T_c$ from the normal state, which is a sign of 2D system. Near $T_c$, similar character has also been reported by Artemento et al. [13], who have observed a Nelson-Kosterlitz jump [14] in current-voltage (IV) characteristics. Lately, Pradhan et al. [16] showed that an external magnetic field along the c-axis washed out the feature of the NK jump, which is as predicted by the KT theory. Martin et al. [15] have observed an exponential square root singularity and power-law dependence in consistent with previous findings.

On the c-axis, interlayer interactions have been extensively studies in crystals at temperatures below $T_c$. Kleiner et al. [17] have found evidence of Josephson interaction in both dc and ac experiments [18]. The temperature dependence of the dc critical current indicates a superconductor-insulator-superconductor (SIS) type Josephson tunneling junction [19], which is consistent with the electron tunneling picture proposed by Anderson and Zou. This critical current was also found to modulate at a periodicity of ~ 500G in an external magnetic field along the ab-plane. It is interesting to note that they further demonstrated that the thickness of the insulating layer has to be ~15Å, which is exactly the spacing between CuO of the bilayers as determined from X-ray, in
order to give the 500G.

The discoveries of the 2D phase transition and the Josephson interaction as mentioned lead us to the first question - how do BSCCO crystals proceed into a non-dissipative state in the possible coexistence of thermal vortices in the ab-plane and the c-axis Josephson interaction in zero field?

To this question, BLK have first shown the existence of thermally excited vortex lines in considering the contribution of entropy of vortex lines. The evidence is that all M(H) curves are found to intersect at a field independent critical temperature $T^*$. This temperature is 3-5K below the GL mean-field temperature $T_{c0}$, while 2K above another critical temperature $T_s$, the spontaneous temperature for thermal vortex lines. Their predictions were confirmed later by Martinez et al. and Brawner et al.

Up to here, we mainly focused on the properties in zero-field. Next, we will overview the electromagnetic behaviors of BSCCO in finite field since this is the third issue to be addressed. The key topics in this area include the crossover from the vortex lattice state to the vortex liquid state, or the vortex glass state in the presence of either intrinsic or extrinsic pinning. Measurements of penetration of magnetic field have also attracted some attention. The ultimate goal for these studies is to find all possible vortex states and map a vortex phase diagram.

Evidence for vortex lattice melting was first claimed by Gammel et al. [20] in a high field experiment by using a mechanical oscillator to measure the friction
motion of vortices. The melting of vortices causes huge dissipation and the
damping of the oscillator. By changing the external field and temperature, they
found a melting line $H_m(T)$ at temperatures well below $T_c$. Using a dc-flux
transformer transport method, Busch et al. [21] and Safar et al. [22] also found
another feature of vortex lattice melting and suggested that vortices in layered
material become more susceptible to distortion in high temperatures and fields.

In a computer simulation, Ryu et al. [24] have shown that the melting line
$H_m(T)$ observed by Gammel et al. can be reproduced when the density of vortices
is increased to cause the destruction of vortex lattice structure. In another
theoretical study, Nelson [25] has proposed that vortex lines in BSCCO could be
twisted and entangled by thermal fluctuations in a thick sample.

The presence of pinning has led many researchers to believe that the
configuration of vortices is not an Abrikosov vortex "lattice" state, but rather a
"glass" state. Fisher [26] first pointed out that the glass state is characterized by
disruption of long range spacial order. It can be observed at low temperature
when pinning strength becomes substantial. It is further predicted that this state
is non-dissipative. Fisher's claim was confirmed later on by Safar et al. [27] in
measuring two critical exponents to be consistent with predictions.

Such a disordered vortex state has also been observed on the surfaces of
crystals and films. By decorating fine magnetic particles on crystals, Murray et al.
[28] have shown pictures of the disordered vortex state at low temperatures. At
high temperatures, the glass state was found to transform into a liquid state, making the identification of individual vortex difficult. A similar effect has also been observed by Harada et al. [29] by using electron-beam Lorentz microscopy.

The studies of pinning nature have led to some other interesting discoveries. Lambardo et al. [30] and Yeshurun et al. [31] have shown the existence of a topological pinning structure - surface barriers. It was found by Chikumoto et al. [32] that these barriers can pin vortices more effectively at high temperatures than bulk defects.

Recently Schilling et al. [33] and Brawner et al. have extended the investigation of vortex dynamics to temperatures very near \( T_c \) by using a Hall probe to measure the difference between applied field and the field near the surface of crystals. The difference reflected the entrance of vortices and mobility of vortices in crystals. They discovered that when vortices were highly mobile, pinning diminished. The diminish caused the disappearance of irreversibility in a sweeping field. They concluded their study with a vortex phase diagram and highlighted on the "reentrant" behavior where the irreversibility intrudes into the high temperature and low field region as shown in Fig. 1.1, where above \( T_s (~85K) \) in the field of 1G to 3G. This study motivates us to reexamine the phase diagram near \( T_c \) by using transport methods.
Figure 1.1 Vortex phase diagram suggested by Brawner et al. [3] for BSCCO near the transition.
1.3 Review of theories and models

1.3.1 Phase transition and vortex phase diagram of a 2D superconductor

As the 2D phase transition has been well demonstrated in CuO bilayers, I shall give a concise description of the extended Kosterlitz-Thouless theory which has been established on thin films and list key equations based on the works of Beasley, Mooij, and Orlando [34], Mooij [35], and Minnhagen [36].

According to the theory, the superconducting transition in thin films completes in a temperature interval $\Delta T$. In the temperature interval, films are still dissipative because of the presence of thermally excited topological defects. Conceptually, these defects like vortices with normal cores at the Ginzberg-Landau (GL) length $\xi$, surrounded by circulating supercurrents at a characteristic length

$$\lambda_\perp = \frac{\lambda^2}{d} \quad (1-1)$$

found by Pearl [37], where $\lambda$ is the London penetration depth, and $d$ is film thickness. For films with thickness $d < \lambda$, $\lambda_\perp$ can be quite large and compared to film size. It is believed that these thermal vortices are generated randomly in films.

These vortices can be in the state of either pairing or free. At low temperatures without external perturbations they are paired. Pearl found that the interaction energy for the pairing, at short distance, $\xi_{ab} < r < \lambda_\perp$, is
\[ U(x) = 2q^2 \ln \left( \frac{x}{\xi_{ab}} \right) \]

(1-2)

where \( q = \frac{\pi \hbar^2 /2m}{h} \) and \( n_s \) is the supercurrent density. The paired vortices are composed of vortices and antivortices and move together. When external perturbations like temperature, current and magnetic field is so strong that these pairs are dissociated into two free vortices. The dissociation by temperature is due to thermal motion. For \( T_c < T < T_{\infty} \), Halperin and Nelson [38] have defined a thermal characteristic length

\[ \xi = a \exp \left\{ \frac{b(T_{\infty} - T_c)}{(T - T_c)^{1/2}} \right\} \]

(1-3)

to describe the status of vortices, where \( a \) and \( b \) are constants of order unity, \( \xi \) is the GL coherence length, \( T_c \) is the Kosterlitz-Thouless transition temperature and \( T_{\infty} \) is the GL mean-field temperature. From the above equation, one can see that at \( T_c \), \( \xi \) is infinite indicating that all vortices are paired, while for \( T > T_c \), \( \xi \) becomes finite implying that some vortices are free. In between \( T_{\infty} \) and \( T_c \), films consist of bound and free vortices like plasma. The existence of free thermal vortices at temperatures between \( T_c \) and \( T_{\infty} \) lead to the broaden of the resistive transition when a fixed current is applied. Following the flux flow mechanism of Bardeen and Stephen [39], the film resistance is expected to be

\[ R \propto R_n \exp \left\{ -2\sqrt{B} \left( \frac{T_{\infty} - T_c}{T - T_c} \right)^{1/2} \right\} \]

(1-4)
where $R_n$ is the normal state resistance of a film. At a given temperature between $T_{co}$ and $T_c$, according to Kadin and Epstein et al. [40,41], in an increasing current the voltage across is found to be

$$V \propto 2\pi \xi^2 n_x R_n I$$  \hspace{1cm} (1-5)$$

From this equation, one finds a power law $V = I^{a(T)}$ with a temperature dependent exponent $a(T)$. $a(T)$ has the following temperature dependence

$$a(T) = 1 + 2 \left( \frac{T_{co} - T}{T_{co} - T_c} \right)$$  \hspace{1cm} (1-6)$$

according to Hebard and Fiory [42]. This equation shows that $a(T)$ equals 3 at $T_c$ dropping to 1 just above $T_c$, and follows a linear dependence at temperatures below. The sharp change of $a(T)$ at $T_c$ is also known as the Nelson-Kosterlitz universal jump.

The 2D nature of films can also be studied in an external field normal to the surfaces. Meissner screening currents can appear in the films with finite size. Fiory, Hebard, and Glaberson [43] found that when the film width $W$ is less than $\xi_\perp$, the screening current is

$$I_w = \frac{4\pi e}{h} K_T K(l_w)$$  \hspace{1cm} (1-7)$$

where $l_w \sim \ln(W/\xi)$ is the depairing length and $K(l)$ is the Kosterlitz-Thouless reduced stiffness constant and $K(l) \sim (1/\pi)(2 + l^{-1})$ [44].
Figure 1.2 Vortex phase diagram of a two dimensional superconductor. The circles are vortices with H pointed outward.
Doniach and Huberman [45] have shown a vortex penetration field

$$H_{c1} = \frac{4\Phi_0}{\eta^2} \ln(\eta/\xi)$$  \hspace{1cm} (1-8)

associated with the screening current $I_w$ where $\Phi_0$ is the flux quantum.

When an external magnetic field is increased above $H_{c1}$, it can penetrate films, screening paired vortices and depress $T_c$. Doniach and Huberman have found the relation between $T_c$ and the polarizability $\epsilon(\infty, T_c)$ of the vortex plasma

$$k_B T_c = \frac{\xi^2}{\epsilon(\infty, T_c)}$$  \hspace{1cm} (1-9)

The polarizability $\epsilon(\infty, T_c)$ increases as the density of free vortices increases. In the plasma, Fisher [46] and Nelson [25] have demonstrated that as the vortex density increases, the lattice structure melts into a liquid phase when thermal displacement $\Lambda$ of each vortex is on the order of the vortex spacing $d$ i.e.,

$$\Lambda = d$$  \hspace{1cm} (1-10)

where $\Lambda = (8\pi^2 D k_B T/\Phi_0 H_c)^{1/2}$, $D$ is sample thickness, and $d \approx (\Phi_0/H)^{1/2}$. Using the above equation, one can correlate the melting and penetration fields

$$H_m(T) = H_{c1}(T) - \frac{H_{c1}(T)}{T}$$  \hspace{1cm} (1-11)

Given the $H_{c1}(T)$ and $H_m(T)$ lines, Nelson have mapped out a vortex phase diagram as shown in Fig. 1.2. In the Meissner region, $H < H_{c1}$, films are
diamagnetic with no magnetic vortices induced in it. In the mixed state, \( H > H_{c1} \), magnetic vortices form a lattice state at low temperatures, while a liquid state at high temperatures. The density of vortices in the mixed state is proportional to the applied field \( H \)

\[
n_f \propto \frac{H}{\Phi_0}
\]

When external field is very high, reaching \( H_{c2}(T) \), the upper critical field, the normal cores of vortices overlap and films become completely normal.

1.3.2 Josephson coupling model for BSCCO and predictions

Here we introduce a very popular model to simulate BSCCO at temperatures below \( T_c \). As proposed by Lawrence and Doniach (LD) \[23\], this material can be viewed as being made of superconducting CuO bilayers coupled by the Josephson interaction. The Hamiltonian for such system is

\[
H = \frac{\alpha H_c^2}{8\pi} \sum_x \int d^2 \rho \left\{ |\xi_{ab}(T) (\nabla_{ab} - i2eA_{ab}) \psi_x|^2 + \left[ 1 - \frac{T}{T_c} \right] |\psi_x|^2 + \frac{1}{2} |\psi_x|^4 \right. \\
- \left. g \exp \left[ 2ie \int_{\mathbb{Z}_n} dz \cdot A_x \right] \psi_{x+1} - \psi_x |^2 \right\} + \frac{1}{8\pi} \int d^3 x \ B^2(x)
\]

which is a sum of layer kinetic energy (gradient and vector potential terms) and
Figure 1.3 Schematic diagram of interlayer coupling of thermally excited vortices.
interlayer Josephson energy (g coupling term). \( \Phi_z \) is the z component Ginzberg-Landau (GL) wave function; \( \xi_{ab} \) the is ab-plane GL coherence length; \( H_c \) is the thermodynamic critical field; \( \alpha \) and \( \beta \) are constants; and \( B \) is magnetic induction.

Ryu et al. have applied this model on BSCCO to find the interlayer Josephson energy dominates, 10 times larger than the kinetic (magnetic) energy in zero field. Jensen and Minnhagen [47] have concluded that all KT features were still observable in BSCCO at high currents. As a result of the interlayer Josephson interaction, they speculated that critical current \( I_c \) might vanish at temperatures slightly above \( T_c \).

Horovitz [48] has shown that there are three transitions as results of the finite interlayer Josephson coupling: the fluxon transition on the c-axis at \( T_f \) that corresponds to \( 2\pi \) phase change from bilayer to bilayer; the KT transition on the ab-plane that appears at \( T_v \) below \( T_f \); and a 3D transition temperature that occurs at \( T_c \) between \( T_f \) and \( T_v \).

By adding a thermal entropy term to the Hamiltonian, BLK have found the line energy for a vortex

\[
\epsilon_I(T) = \frac{\Phi_0^2}{16\pi^2\lambda_{ab}^2} (\ln \kappa + 0.5) - \frac{T}{S} \ln \frac{32\pi T \kappa^2 \lambda_J^2}{\Phi_0^2 \alpha \ln (\lambda_J/\xi_{ab})}
\]

(1-14)

where \( s \) is the interlayer spacing, \( \alpha \) is a constant of the order unity, and \( \lambda_J \) is the Josephson penetration depth. This equation yields a negative \( \epsilon_I \) at temperatures
between $T_g$ and $T_\infty$ suggesting that thermal vortices are favored, created at cost of no energy, while they are not favored at $T$ above $T_\infty$. Such picture of thermally created vortex-antivortex lines is shown in Fig 1.3.

1.3.3 Thermal fluctuations in Josephson coupled layered superconductors

Thermal fluctuations are known to modify the IV curves in Josephson tunneling junctions. Physically, these fluctuations disturb the phase coherence of supercurrents between superconducting electrodes, and cause dissipation. Ambegaokar and Halperin (AH) [52] have shown that the voltage induced across the electrodes is proportional to the phase changing rate in time

$$\frac{d\Theta}{dt} = 2eV \quad (1-15)$$

Ivanchenko and Zil'berman [53] has further established a resistance-capacitance-shunted-Josephson (RCSJ) junction model to simulate the current-voltage relationship in real samples as shown in Fig. 1.5. This model includes a true Josephson junction with a critical current $I_c(T)$, a resistance $R$ for quasiparticle scattering, a capacitance $C$ for electrical contacts, a current source $I$ and a time dependent fluctuator $L(t)$ due to thermal fluctuations. The kinetic equation is

$$C\frac{dV}{dt} + I_c(T) \sin \Theta + \frac{V}{R} = L(t) + I \quad (1-16)$$
Figure 1.5 Electrical circuit diagram of a direct-current biased Josephson tunneling junction.
AH have solved the above equation and found an analytical solution

\[
\frac{V}{I_c R} = \frac{4\pi}{\gamma} \left( e^{\gamma x} - 1 \right)^{-1} \left[ \int d\theta f(\theta) \left\{ \int d\theta' \frac{1}{f(\theta')} \right\} + \int d\theta \int d\theta' \frac{f(\theta)}{f(\theta')} \right]^{-1}
\]

(1-17)

where \( f(\theta) = \exp(-U(\theta/T)) \), \( U(\theta,T) = -\gamma T(x\theta + \cos \theta)/2 \), \( x = I/I_c(T) \), \( \gamma = \hbar I_c(T)/eT \). In the limit of low currents, \( x < 1 \), and \( \gamma >> 1 \), this solution can be simplified as

\[
v = 2(1-x^2) \exp\left\{ -\gamma \left[ (1-x^2) + x \sin^{-1} x \right] \right\} \sinh \left( \frac{\pi x}{2} \right), \gamma large, x < 1
\]

(1-18)

We shall use the above equation to explain the c-axis current-voltage data.

1.3.4 Normal state anisotropic resistivity model

In this section, we discuss the derivation of resistivities \( \rho_{ab}(T) \) and \( \rho_c(T) \) in the Ohmic regime using a six-contact geometry. In our experiments, the quantities measured are electrical potential differences. To obtain \( \rho_{ab}(T) \) and \( \rho_c(T) \), we need to solve the 3D Laplace equation

\[
\nabla \cdot J = \frac{1}{\rho_{ab}} \frac{\partial^2 V}{\partial x^2} + \frac{1}{\rho_{ab}} \frac{\partial^2 V}{\partial y^2} + \frac{1}{\rho_c} \frac{\partial^2 V}{\partial z^2} = 0
\]

(1-19)

The details of solving \( V(x,y,z) \) as functions of \( \rho_{ab}(T) \) and \( \rho_c(T) \) for a sample of size \( L \times W \times D \) under different experimental configurations are given in the appendix.
Here we list the main results. For the ab-plane measurements where current is applied to the top surface (see Fig. 2.6a and c), we find

\[
V_{ab}(x, y) = \frac{32 I k}{\pi} \sum_{n=1}^{\infty} \frac{\cos\left(\frac{n\pi}{4}\right) \sin\left(\frac{n\pi x}{L}\right)}{n^2 \pi^2 \tanh(p \pi n \frac{D}{L})} + \frac{256 I k}{\pi} \sum_{n,m=1}^{\infty} \frac{\cos\left(\frac{m\pi}{4}\right) \sin\left(\frac{m\pi x}{L}\right) \sin\left(\frac{n\pi y}{L}\right) \cos\left(\frac{m\pi y}{W}\right)}{mn \pi^3 \left[n^2 + \left(\frac{mL}{W}\right)^2\right]^{1/2} \tanh(p \pi \left[n^2 + \left(\frac{mL}{W}\right)^2\right]^{1/2} \frac{D}{L})}
\]

(1-20)

and

\[
V_{a}(x, y) = \frac{32 I k}{\pi} \sum_{n=1}^{\infty} \frac{\cos\left(\frac{n\pi}{4}\right) \sin\left(\frac{n\pi x}{L}\right)}{n^2 \pi^2 \sinh(p \pi n \frac{D}{L})} + \frac{256 I k}{\pi} \sum_{n,m=1}^{\infty} \frac{\cos\left(\frac{m\pi}{4}\right) \sin\left(\frac{m\pi x}{L}\right) \sin\left(\frac{n\pi y}{L}\right) \cos\left(\frac{m\pi y}{W}\right)}{mn \pi^3 \left[n^2 + \left(\frac{mL}{W}\right)^2\right]^{1/2} \sinh(p \pi \left[n^2 + \left(\frac{mL}{W}\right)^2\right]^{1/2} \frac{D}{L})}
\]

(1-21)

where \(x\) varies from 0 to \(L/2\) and \(y\) from 0 to \(W\), \(n\) is an odd positive integer, \(k = (\rho_c \rho_{ab})^{1/2}\), and \(p = (\rho_c / \rho_{ab})^{1/2}\).

For our c-axis measurements (see Fig. 2.6b) where current is passed through the top and bottom surfaces, we find
\[ V_c(x,y) = \sum_{n=1}^{\infty} \frac{16 k I \sin(\frac{m\pi}{4}) \cos(\frac{m\pi y}{W})}{m^2 \pi^2 L} \left[ \cosh\left(\frac{p_n \pi D}{W}\right) - 1 \right] \left[ \frac{1}{\sinh\left(\frac{p_n \pi D}{W}\right)} \right] \]

\[ + \sum_{n=1}^{\infty} \frac{16 k I \sin(\frac{n\pi}{4}) \cos(\frac{n\pi x}{L})}{n^2 \pi^2 W} \left[ \cosh\left(\frac{p_n \pi D}{L}\right) - 1 \right] \left[ \frac{1}{\sinh\left(\frac{p_n \pi D}{L}\right)} \right] + \frac{\rho c D}{LW} + \]

\[ \sum_{n, m=1}^{\infty} \frac{128 k I \sin(\frac{m\pi}{4}) \sin(\frac{n\pi}{4}) \cos(\frac{m\pi X}{W}) \cos(\frac{n\pi y}{W})}{nm \pi L W \left[ (n/L)^2 + (m/W)^2 \right]^{1/3}} \left[ \cosh\left(\frac{p_n \pi [(n/L)^2 + (m/W)^2]^{1/2} D}{W}\right) - 1 \right] \left[ \frac{1}{\sinh\left(\frac{p_n \pi [(n/L)^2 + (m/W)^2]^{1/2} D}{W}\right)} \right] \]

where \( x \) varies from 0 to L, and \( y \) from 0 to W.
CHAPTER II
SAMPLE PREPARATION AND EXPERIMENTAL DETAILS

2.1 Introduction

In this chapter, we will describe in detail the process of growing BSCCO compounds, the selection of sample crystals, and the fabrication of electrical leads on samples. We also explain our sample stage and experimental environment. A four-terminal low frequency AC technique for measuring current-voltage and an electrical circuit diagram will be introduced. For quick reference, in Table 2.1 we list sample sizes, ab-plane transition temperature $T_{c}^{ab}$, measured voltage signals, and 300K values of $\rho_{ab}$ and $\rho_{c}$ of our samples.

2.2 Sample preparation

To make BSCCO(2212) crystals, we started with a non-stoichiometric 99.9% purity oxide powders $\text{Bi}_2\text{O}_3$, $\text{CuO}$, $\text{SrCO}_3$, and $\text{CaCO}_3$ at atomic weight percentage of 22.4%, 32%, 26.9% and 18.7%, respectively, following the recipe of Imer et al. [54]. The powders were grounded in a mortar for 2-3 hours into uniformly mixed fine particles. Three grams of powders were placed in a gold crucible of 3cm in diameter and 5cm in height. The crucible was then placed into
Table 2.1 Summary of parameters for BSCCO crystals

\[ \rho_{ab}(300K) = \frac{(V_{ab}WD)}{(I_{ab}L)} \] and \[ \rho_c(300K) = \frac{(V_cLW)}{(I_cD)} \]. Signals \( V_{ab} \), \( V_c \), and \( V_s \) are voltages measured using the configuration in Fig. 2.6. The uncertainty for \( L \) and \( W \) is estimated to ± 0.1mm and \( D \) ± 3\( \mu \)m. The transition temperature \( T_c^{ab} \) for sample #1, #2, and #4 is determined from IV measurements; for sample #3, #5 and #6, \( T_c^{ab} \) is an approximate estimation determined by the temperature at which the measured voltage (at a constant current) drops below the system noise floor. Note that \( \rho_{ab} \) and \( \rho_c \) are estimated based on the voltages and sample dimensions. A more accurate treatment will be shown later in the thesis.

<table>
<thead>
<tr>
<th>Sample</th>
<th>LxWxD (mm)x(mm)x(( \mu )m)</th>
<th>Signals</th>
<th>( T_c^{ab} ) (K)</th>
<th>( \rho_{ab} ) ( \mu )Ωcm</th>
<th>( \rho_c ) Ωcm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.4x0.35x20</td>
<td>( V_{ab} )</td>
<td>84.9</td>
<td>210( \mu )Ωcm</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>0.7x0.5x19</td>
<td>( V_{ab}, V_c, V_s )</td>
<td>84.3</td>
<td>1070( \mu )Ωcm</td>
<td>0.35Ωcm</td>
</tr>
<tr>
<td>3</td>
<td>0.7x0.3x10</td>
<td>( V_c, V_s )</td>
<td>85.8</td>
<td>-</td>
<td>0.8Ωcm</td>
</tr>
<tr>
<td>4</td>
<td>0.7x0.5x10</td>
<td>( V_{ab} )</td>
<td>85.5</td>
<td>350( \mu )Ωcm</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>0.9x0.5x20</td>
<td>( V_s )</td>
<td>87.8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>1x0.4x20</td>
<td>( V_s )</td>
<td>85.5</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
a tube furnace for heat treatment. The heat treatment was conducted in an atmosphere of flowing oxygen (99.9% purity) at a rate of one standard cubic foot per hour.

Fig 2.1 shows the temperature chart of the heat treatment in time. The crucible temperature was first ramped to 800°C at 200°C/h, then to 920°C at 20°C/h, and dwelled at 920°C for 5 hours. After the ramping and dwelling process, the temperature was ramped down at a very low rate of 1°C/h to 850°C, then at 5°C/h to 800, at 100°C/h to 500°C, and finally cooled to room temperature. The whole thermal cycle took about 100 hours.

This method of growing compounds is also known as powder metallurgy or solid-state reaction. Detail description was given Iyer and Yakhmi in Ref.[55]. This was one of the most popular methods adopted for the synthesis of high $T_c$ superconductors. The growing of 2212 crystals occurs at about 885°C as Tarascon et al.[56] and Lee et al. [57] have shown that at that temperature the 2212 phase starts to melt (or solidify). It was found to be a stable phase at lower temperatures. It is common to find other phases using this method. For example, under an electron microscope, Zandbergen and Groen [58] identified Bi$_2$Sr$_2$CaO(2201) and Bi$_2$Sr$_2$Ca$_2$Cu$_3$O(2223) phases.

After the thermal cycle, we found micaceous sheets randomly extended from a black glassy mass in the crucible. The black compounds were taken out the crucible mechanically using a screw-driver.
Fig. 2.1 Time chart of crucible temperature for fabricating crystals.
We used an optical microscope to select crystals. With this tool, we could avoid some common defects such as twin boundaries, stacking faults and intergrowths reported by Zandbergen et al. [59], and Ikeda et al. [60]. We first examined the surface of a piece compound to find flat and mirror-like area and then used a razor blade to cleave out this region. This method is reliable as most our samples were free of twin boundaries under the examination of a scanning tunneling microscope (STM) and a scanning electron microscope (SEM).

Cleaving was rather easy as long as pressure was applied along the ab-plane. After several cleaving steps, we often had many thin pieces of crystal with thickness ranging from 5 to 20μm. The ultimate thickness of crystals was limited by the fragileness of this material. These irregular thin crystals were then cut into squares of millimeter sizes. To ensure our sample oxygen homogeneity, these crystals were reannealed in a pure oxygen atmosphere at 500-600°C for more than 24 hours.

2.3 Electrical contacts and sample stage

We put up to six electrical contacts on a sample. The fabrication of electrodes is described as follows.

Four-contact sample

We used MgO crystals polished on one side as substrates to mount our
samples as shown in Fig. 2.2a. The 1mmx1mmx0.5mm substrates have a thermal expansion coefficient similar to the samples, which minimizes the thermal stress on samples during thermal cycles.

To make electrical contacts, silver adhesive (ACME 3022) was pasted on four edges of a sample. As shown in Fig. 2.2a, electrical conduction was achieved by firing the silver at 500-600°C for 1-2 hours in air. The high temperature firing makes silver diffuse through the insulating surface layers of a sample. This insulating layer has been confirmed by Liu et al. [61] and has always been of concern in scanning tunneling measurements. After the firing, we had an electrical contact resistance less than 5Ω.

**Six-contact sample**

The six-contact fabrication is more complicated. Fig. 2.2b shows the configuration of a six-contact sample. Two electrical contacts were placed on the secondary layer and four on the primary layer of a sample. First we put two gold pads on a substrate, then we mounted the sample on the top of the gold pads, and finally four contacts using 50 μm gold wires were made on the top of the sample.

**Sample stage**

Fig. 2.3 shows the copper sample stage we used for all measurements. Our samples were mounted on the top of the stage. The thermal link between the
stage and samples was provided by vacuum grease (Apiezon N). At the bottom, a stainless steel joint provided thermal insulation between the stage and the rest of the probe. The copper pins were for electrical connections. A carbon-glass thermometer (model CGR-1-200) was placed right underneath the sample. A heater made of high resistance Evanohm wire with a total resistance of 60 Ω was placed next to the thermometer. This heater provided stabilized temperatures from 4K to 100K with a dc current up to 1mA. When enclosed in a vacuum-sealed can, this stage gave us a temperature stability of ~ 0.05K and resolution ~ 0.2K at 100K.

For measurements in a magnetic field, we used a superconducting magnet which was able to generate a field up to 6.5 Tesla. For zero-field measurements, a superconducting lead foil was wrapped around the sample stage to shield the earth's field, giving a residual field less than 50mG.

2.4 Transport measurements and electrical circuit diagram

We applied a low frequency (16.9Hz) lock-in technique to conduct all resistive and current-voltage measurements. Fig. 2.4 shows the electric circuit diagram. On the left side of this circuit is a closed loop consisting of a voltage source, a ballast resistor, a current monitor resistor and the sample. The 10V
Figure 2.2 Sample contact geometries, four-contact(a) for sample #1, six-contact(b) and substrate.
Figure 2.3 Structure of sample stage.
Figure 2.4 Electrical circuit diagram.
Figure 2.5 Four-contact measurement of the ab-plane resistance and IVs of sample #1. See also Fig. 2.2a.
Figure 2.6 (a) Six-contact measurement of the ab-plane IVs, (b) of the c-axis IVs, (c) of the secondary voltage. See also Fig. 2.2b.
voltage source, which was made by Calabrese [62] provided sample currents. This voltage source, with an output impedance of 100Ω, had a maximum output current of 100mA. The ballast resistors with ten possible values from 0Ω to 10MΩ gave us another way of tuning sample current. The combination of the voltage source and the ballast resistors provide sample currents from 50mA to 1μA.

The sample current was measured across the 1Ω current-monitor resistor R with a PAR 128A voltage amplifier. The sample voltage was monitored by using a 1:100 transformer (EG&G 1900) and a PAR 124A voltmeter. This electrical set up yields 1nV and 1μA resolution. The sample temperature was measured using the carbon-glass thermometer with a potentiometric conductance bridge (model PCB). All current, voltage and temperature data were then registered in a DATA 6000 digital meter. A function generator was used to the synchronize the current source and all meters.

Combining the four-, six-contact sample and the electrical circuit, we managed to measure current-voltage (IV) characteristics in four ways. Fig 2.5 shows the IV measurements for a four-contact sample where current was sent into the sample from the end surfaces and voltage was measured at the side surfaces. Fig. 2.6 shows a six-contact sample and three possible ways of measuring IV. In Fig. 2.6a, a current I is injected into the top surface (contacts A and B) and $V_{ab}$ is recorded on the same surface (contacts C and D). In Fig. 2.6b, a current I is passed from the top to the bottom surfaces (contacts A and E) and $V_c$ is measured
Figure 2.7 Raw $V_t$ data ($\nabla$) and the averaged ($\square$) of sample #3 at 0.5mA in $H=0$. 
between them (contacts B and F). In Fig. 2.6c, a current I is applied on the top surface (contacts A and B) and $V_s$ is measured on the bottom one (contacts E and F).

Near $T_c$, we often recorded multiple data points at a given temperature because we were limited by our temperature resolution ~ 0.2K. To present a clear picture of our data, we simply averaged these points at the same temperature. Fig. 2.7 shows the data before and after the averaging. The averaging was done with a program in BASIC listed in the appendix.

Here, we also note that we tested many samples because the electrical contacts tended to deteriorate after several thermal cycles. Thermal stress broke these contacts as layers could be readily peeled from crystals. We tried to protect these contacts by coating our samples with a thin layer of GE varnish. Despite this effort, we still intermittently lost contacts. Once the contacts were bad, they were not repairable.
CHAPTER III
NORMAL STATE RESISTIVITY

3.1 Introduction

In this chapter, we will present the derivation of the normal state resistivities of sample #1 and #2. For sample #1, we use the conventional method to derive the ab-plane resistivity $\rho_{ab}(T)$. For sample #2, an anisotropic 3D anisotropic resistivity model was used to calculate $\rho_{ab}(T)$ and c-axis resistivity $\rho_{c}(T)$. We then compare our results to some representative values reported previously by other research groups.

3.2 Data

Fig. 3.1 presents the normal state resistance and $\rho_{ab}$ of sample #1 measured at 0.5mA. Fig. 3.2 shows the voltages $V_{ab}(T)$, $V_{c}$ and $V_{s}(T)$ and 3D model fit of $V_{s}$ for sample #2. This fit is based on the model of solving a 3D Laplace equation. The details of solving this equation under our experimental conditions are given in appendix B. We use the iterative Levenberg-Marquardt numerical method in Mathcad program to find the parameters k and p in equations (1-20) and (1-22) which provide the best fit to the measured $V_{ab}$ and $V_{c}$.
From $k$ and $p$ the resistivities are simply found from the relations $k = (p_c p_{ab})^{1/2}$ and $p = (p_c / p_{ab})^{1/2}$. Given the derived $p_{ab}(T)$ and $p_c(T)$ and equation (1-21), the $V_s$ was determined uniquely. For this calculation, all the voltages are normalized to 0.1mA since the actual measurement currents are different for each voltage; 0.5mA for $V_{ab}$, 0.4mA for $V_s$ and 0.1mA for $V_c$. The same calculations can be applied on equations (1-20) and (1-21) to derive $p_{ab}(T)$, $p_c(T)$ from voltages $V_{ab}$ and $V_c$. Fig. 3.3 shows both $p_{ab}(T)$ and $p_c(T)$ derived from $(V_{ab}, V_s)$ and $(V_{ab}, V_c)$ for sample #2.

3.3 Discussion

The derivation of sample #1 resistivity is straightforward. Because the current distribution in the sample is uniform, one can use the following simplified equation as demonstrated by Busch et al. [21] to obtain $p_{ab}(T)$

$$\rho = \frac{R W D}{L}$$

(3-1)

where $L$, $W$, $D$, and $R$ are sample length, width, thickness, and resistance. The resulting $p_{ab}(T)$ is presented in Fig. 3.1. There are several features in the normal state resistivity we like to point out. The room temperature value ~ 210$\mu\Omega$cm is comparable to that ~ 150$\mu\Omega$cm reported by Cooper, Forro, and Keszei [11]. The rounding feature above 100K is well known, and has been interpreted as results of thermal fluctuations (see Mun et al. for example). The superconducting
Figure 3.1 Normal state ab-plane resistivity of sample #1 for I=0.5mA. The dashed line is to extract zero temperature resistivity. Inset shows the resistance in the normal state.
Figure 3.2 Temperature dependence of $V_{ab}$, $V_c$ and $V_x$ of sample #2 normalized to a current 0.1mA and 3D model fit for $V_x$ using $V_{ab}$ and $V_c$. 
Figure 3.3 Normal state resistivities of sample #2 derived from pair voltages \((V_{ab}, V_c)\) and \((V_{ab}, V_c)\) using 3D model.
Table 3.1 Summary of previous and our resistivities results for BSCCO

The values of $\rho_c$, $\rho_{ab}$ and $\rho_c/\rho_{ab}$ are at 100K. $\rho_{ab}(T=0)$ is an extrapolated value, and $\Delta T$ is defined as the temperature between 90% and 10% of normal state $\rho_{ab}$ in transition. Note that the $\rho_c$, $\rho_{ab}$ (in contrast to Table 2.1) for sample #2 were computed from the 3D model. Errors are from uncertainty in measured sample dimensions.

<table>
<thead>
<tr>
<th>Authors</th>
<th>$\rho_c$ (Ωcm)</th>
<th>$\rho_{ab}$ (μΩcm)</th>
<th>$\rho_c/\rho_{ab}$</th>
<th>$\rho_{ab}(T=0)$</th>
<th>$\Delta T$(K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Martin et al. [9]</td>
<td>5</td>
<td>40</td>
<td>$1 \times 10^5$</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>Cooper et al. [11]</td>
<td>12</td>
<td>50</td>
<td>$2.4 \times 10^5$</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Briceno et al. [49]</td>
<td>1.2</td>
<td>300</td>
<td>$4 \times 10^3$</td>
<td>100</td>
<td>3</td>
</tr>
<tr>
<td>Busch et al. [21]</td>
<td>7</td>
<td>100</td>
<td>$7 \times 10^4$</td>
<td>-</td>
<td>3~6</td>
</tr>
<tr>
<td>Sample #1</td>
<td>-</td>
<td>60±10</td>
<td>-</td>
<td>15±10</td>
<td>4</td>
</tr>
<tr>
<td>Sample #2</td>
<td>1.5±0.3</td>
<td>400±100</td>
<td>3500±400</td>
<td>200±110</td>
<td>4</td>
</tr>
</tbody>
</table>
transition width is sharp ~ 3K, defined as the temperature interval between 10%-90% of \( \rho_{ab} \) in transition. The extrapolated value at \( T = 0 \) (see the dashed line in Fig. 3.1) is low at ~ 20\( \mu \Omega \)cm.

For sample #2, the procedures of obtaining resistivity are more complicated as mentioned in the section 3.2 because of the nonuniform current distribution in the sample. The resulting \( \rho_{ab}(T) \) and \( \rho_c(T) \) are shown in Fig 3.2. In the calculation the contact positions for \( V_{ab} \) on the primary layer were placed at (0.35mm, 0.36mm, 19\( \mu \)m), and (-0.35mm, 0.36mm, 19\( \mu \)m). For \( V_s \) the positions were at (0.35mm, 0mm, 0\( \mu \)m) and (-0.35mm, 0mm, 0\( \mu \)m) (see Fig. A-1). These positions are chosen close to the current pads to pick up the strongest voltage signal. The resulting \( \rho_{ab}(T) \) and \( \rho_c(T) \) are presented as solid symbols in Fig. 3.3.

We also use similar method to derive resistivities by solving eq.(1-20) and eq.(1-22) simultaneously for a given pair of voltages \( V_{ab} \) and \( V_c \). The positions for \( V_{ab} \) are the same as above, while for \( V_c \) they are at (0.68mm, 0.05mm, 19\( \mu \)m) and (0.68mm, 0.05mm, 0\( \mu \)m). As shown in Fig. 3.3, the results obtained from the latter method shows almost identical values to those of the former method in the normal state with an deviation of ~ 5%. This analysis clearly demonstrate that in the normal state this material can be fully characterized as an anisotropic Ohmic media. Note that \( \rho_{ab}(T) \) shows a metallic character, while \( \rho_c(T) \) is semi-metallic at temperatures below ~ 150K, but metallic above. The mixing of metallic and semiconducting behavior in the normal state \( \rho_c(T) \) is commonly seen and it is
generally attributed to either thermal fluctuations or the chemical concentration of oxygen. The anisotropy $\rho_c/\rho_{ab}$ ratio increases from $\sim 1.4 \times 10^3$ to $\sim 3 \times 10^3$, when the sample temperature is cooled down from 300K to 100K. The normal state $\rho_c$ values calculated from the 3D model is found to be 4-2 times larger than those from the conventional method: at 300K the former is $\sim 1.4 \Omega\text{cm}$ while the latter is $\sim 0.35 \Omega\text{cm}$; at 100K the former is $\sim 1.5 \Omega\text{cm}$, while the latter is $\sim 0.7 \Omega\text{cm}$. That indicates that resistivities can easily be underestimated by the same factor, if the effect of uniform current distribution in samples is not properly considered.

To compare our results with those reported previously, we summarize our results and those in Table 3.1. From this table, we find that the $\rho_{ab}(100K)$ for sample #1 is low, close to that of Martin et al. and Cooper et al. The $\rho_c(100K)$ and $\rho_c(100K)/\rho_{ab}(100K)$ values for sample #2 are quite low, while the value of $\rho_{ab}(100K)$ is very high. This values, however, are close to those of Briceno et al. The uncertainties in our results come from the uncertainty in sample sizes; for example an increase of the thickness $D$ by $1 \mu\text{m}$ results in an increase of $\rho_{ab}$ by $\sim 30 \mu\Omega\text{cm}$ and decrease of $\rho_c$ by $\sim 0.1-0.2 \Omega\text{cm}$ at 300K.

While the high $\rho_{ab}$ value, as well as the unusual behavior of $\rho_c(T)$ for sample #2 in the normal state may lead one to question our sample quality, we feel that our samples are among the high quality crystals available so far. As mentioned in the previous chapter, each of our samples was inspected under a microscope to ensure that there were no visible cracks, grain boundaries, or other
obvious imperfections. We did not attempt to verify the crystallography or chemical composition of our samples (e.g., by X-ray, Rutherford backscattering). Such measurements are deemed unnecessary since we used a well-established preparation technique, and also because chemical composition and crystallography information is often not a sensitive measure of the electrical quality of samples. With regard to transport properties, the measured transition temperature for our samples varies from 83-90K, depending on the state of oxygenation. For example, the two samples used in the well-known work of Safar et al. [22] had approximate transition temperatures of 83K and 93K. (Actually, the reported 93K appears to be anomalously high for the Bi:2212 phase.) The width of the transition region is a good measure of sample quality, since inhomogeneities or uneven oxygenation tend to result in a broadened transition. Using a standard 10%-90% criterion, we estimate the transition width of the sample #2 (our sample for which the most comprehensive data set is available) to be about 2K. For purposes of comparison, the width of the two Safar et al. samples was 5K and 3K.

Similarly, the absolute resistivities $\rho_c$ and $\rho_{ab}$ also show wide sample-to-sample variations. Our sample 2, for example, had $\rho_{ab}(100K) \approx 400\mu\Omega\cdot\text{cm}$, which is higher than that reported by several authors (see Table 3.1). (Note, however, that some reported number are probably unreliable; for example, Martin et al. [9] reported measurements of $\rho_{ab}$ which lead to an extrapolated zero-temperature resistivity which is negative. Authors who fail to account properly for the
nonuniform current distribution in their samples also miscalculate the magnitude of the resistivities.)

3.4 Conclusion

In conclusion, we studied the normal state transport properties of BSCCO crystals by measuring voltages in various faces of crystals with multiple electrical leads. Quantitative analysis on the voltages of sample #2 indicated that the normal state transport behavior of BSCCO crystals can be described by the classical theory based on a Laplace equation.
CHAPTER IV
SUPERCONDUCTING TRANSITIONS IN ZERO MAGNETIC FIELD

4.1 Introduction

In this chapter, we address the issue of the superconducting transition on the ab-plane and c-axis of BSCCO by looking into current-voltage characteristics [63].

4.2 Data

Fig. 4.1 shows the $\rho_{ab}(T)$ from eq.(3-1) of sample #1 at I=0.5mA near $T_c$. Fig. 4.2 presents the current-voltage characteristics of the sample near transition; nineteen IVs were taken between 86.2K and 84K at an average interval of ~ 0.1K. Fig. 4.3 shows the temperature dependence of the power law exponent of sample #1. Fig. 4.4 presents the temperature dependence of the exponent of Artemenko et al. Fig. 4.5 present the ab-plane IVs of sample #2. Fig. 4.6 exhibits the temperature dependence of the exponent of sample #2. Fig. 4.7 illustrates the c-axis IVs of sample #2. Fig. 4.7 shows the temperature dependence of the c-axis critical current of sample #2.
4.3 Discussion

Since we have a high quality sample #1, we are attempting to reexamine the resistive transition on the ab-plane. Here, we apply a low current of 0.5mA to examine the resistive transition and we find an exponential square-root dependence in Fig. 4.1. We then fit the $\rho_{ab}$ with the KT theory by using eq.(1-4) with parameter $b = 1.2$. From the fitting line, we identify two critical temperatures; the mean-field transition temperature $T_{co} \sim 86.4K$ and the KT temperature $T_c \sim 84.8K$.

As a second check, we examine current-voltage characteristics. In Fig. 4.2, we find that these IVs show a crossover from high temperature linearity to low temperature nonlinearity at low currents as illustrated by solid lines. The reappearance of the linearity at high currents for those low temperature IV curves is because the sample is driven normal. We analyze these IVs using the power law $V = I^a(T)$. The resulting $a(T)$ is presented in Fig. 4.3. We find that the $a(T)$ shows a jump from 1 to 3 at $\sim 84.8K$, denoted as $T_c$. The mean-field temperature $T_{co}$ is extrapolated to $\sim 86.5K$ from a dashed line. The fitting error is represented by the size of the circles. Incidentally, we find the temperature difference between $T_c$ and $T_{co}$ is $\sim 2K$, very close to the value $\sim 3K$ reported by Martin et al. [15] and Martinez et al. [9].

Our $a(T)$ shows a much clearer "jump" when compared to that of Artemenko et al. [13] in Fig. 4.4. Our jump occurs over a narrower temperature
Figure 4.1 Ab-plane resistive transition of sample #1, measured at 0.5mA.
Figure 4.2 Ab-plane IVs of sample #1. Temperatures are 86.2, 85.4, 85.2, 85, 84.9, 84.8, 84.7, 84.6, 84.5, 84.47, 84.42, 84.37, 84.33, 84.28, 84.24, 84.19, 84.1, 84K.
Figure 4.3 Temperature dependence of exponent $a(T)$ of sample #1.
Figure 4.4 Temperature dependence of exponent $a(T)$ by Artemenko et al. in Ref[13].
range of 0.5K in contrast to 4K. This may be attributed to better sample quality.

Now we study the superconducting transitions in the ab-plane and the c-axis of sample #2. We first discuss the IV data on the ab-plane in Fig. 4.5. The behavior of these IVs are familiar; linear at high temperatures for all currents and nonlinear at low temperatures. Again, we analyze the low-current nonlinearity by using the power law and find evidence of the KT transition. The resulting $a(T)$ in Fig 4.6 shows a more marked jump at $\sim 84.3K$, which is due to the nonuniform current distribution in this sample. For current uniformly distributed in each CuO bilayers (sample #1), we observed an near ideal universal jump [63]. Based on this analysis, we thus define 84.3K as the ab-plane transition temperature $T_{c^{ab}}$.

Similar analysis of the c-axis IVs led us to identify a higher critical temperature. In Fig. 4.7, we find that nonlinearity (solid lines) set in at 86.5K, denoted as $T_{c^c}$. The analysis of temperature dependence of Josephson current density $J_c(T)$ also supported this c-axis transition. As shown in Fig 4.8, one can clearly see that at $\sim 86.5\pm0.1K$ $J_c(T)$ is zero. The calculation of $J_c(T)$ is that at each temperature a critical current $I_c(T)$ was obtained by extrapolating the solid lines down to 1 nanovolt, and divided over the sample area LW. The uncertainty in the transition temperature is because of the nonuniform current distribution (see Fig. A-3 in Appendix for the nonuniform current distribution in this sample). In doing so we assumed that current density is uniform over the area which yields an error in $J_c(T)$ within a factor of $\sim 3$. 
Figure 4.5 Ab-plane IVs of sample #2. Temperatures are 87.6, 87.1, 86.8, 86.6, 86.4, 86.2, 85.9, 85.7, 85.5, 85.2, 85, 84.7, 84.4, 84.2, 84K.
Figure 4.6 Temperature dependence of exponent $a(T)$ and the $ab$-plane transition temperature for sample #2.
Figure 4.7 C-axis IVs of sample #2. Temperatures are 87.6, 87.1, 86.8, 86.6, 86.4, 86.2, 85.9, 85.5, 85.3, 85.2, 85, 84.7, 84.4, 84.2, 84K.
Figure 4.8 C-axis critical current density and preliminary estimation of resistivity for sample #2.
In an advanced analysis, we estimated of the c-axis resistivity in transition and found consistent results. We use the conventional formula eq.(3-1) for temperatures above $T_c^c$ since IVs are linear, while below to reflect the observed nonlinearity we set $\rho_c(T) = \rho_c(86.5K)V_c(T)/V_c(86.5K)$ at $I=10\mu A$. As shown in Fig. 4.8, we found that $\rho_c$ shows a sharp drop by two orders in magnitude within one Kelvin near $T_c^c$. The finite value of $\rho_c$ below $T_c^c$ is due to thermal fluctuations (linear tails at low currents to be discussed later). The finding of two transitions indicates that the completeness of the superconducting transition in BSCCO crystals is on the ab-plane, although the Josephson coupling along the c-axis occurs at a higher temperature $T_c^c$. This finding is also quantitatively compatible with the theory of fluxon transition by Horovitz [48]. He had predicted that at a temperature higher than the KT temperature, fluxons are created owing to the interlayer Josephson interaction. Here we note that in our earlier $\rho_c$ calculation using the conventional method in Ref. [63] (Figs. 1 and 2a), we overestimated it by a factor of $\sim 3$ and underestimated the point at 86.5K by a factor of $\sim 3$, these mistakes, however, does not alter our main conclusions.

We now discuss the low-current linear tails based on the resistance-capacitance-shunted-Josephson (RCSJ) junction model of Ambegaokar and Halperin in chapter I. We generated a series of IV curves in Fig. 4.9. These solid lines seem to mimic the data very well at low currents. The good fit provides evidence that the Ohmic feature may come from thermal fluctuations.
Figure 4.9 Fit to the c-axis current-voltage characteristics for sample #2 using Ambegaokar-Halperin fluctuation theory.
Figure 4.10 Temperature dependence of fitting parameters $\gamma$ and $I_c$ for sample #2 based on Ambegaokar-Halperin theory.
The fitting parameters $\gamma(T)$ and $I_c(T)$ for producing these solid lines are presented in Fig. 4.10. We find that both $\gamma(T)$ and $I_c(T)$ decrease as temperature is increased. Zero $I_c(T)$ is at $-86.5K$, which once again agrees with $T_c^c$ determined previously. We also notice that $I_c(T)$ determined from the fit is about three times larger than that determined by a voltage criterion as cited by Martin et al. in Ref.[5].

4.4 Conclusion

The superconducting transition in BSCCO crystals was demonstrated through a series of current-voltage measurements. We found the transition was initiated by Josephson coupling between CuO bilayers and complete at the KT temperature when all thermal free vortices were paired. The temperature interval for the transition was found to be $\sim 2K$. This finding led to our next experiment of using a dc-flux transformer technique to test the idea of interlayer coupling of thermal vortices at temperatures between $T_c^{ab}$ and $T_c^c$. 
CHAPTER V
INTERLAYER JOSEPHSON COUPLING OF THERMALLY EXCITED
VORTICES

5.1 Introduction

In this chapter, we address the issue of layered thermal vortices coupled by interlayer Josephson interaction [63]. The method we used for this experiment in Fig. 2.6c is the so-called modified "dc flux-transformer". The original one was used by Giaever [50], Ekin et al. [51] and other researchers to find dissipation on the secondary layer in magnetic fields when one applied a current on the primary layer. The samples used were made of two superconducting films electrically isolated by a thin insulator. In their studies the dissipation on the secondary layer was found to be a direct result of the motion of the Abrikosov vortex lattice. The mechanism is that the vortices on the primary and secondary layers are coupled magnetically so any movement on the primary layer could transfer to the secondary layer if the vortices are not pinned on the secondary layer. We expect similar effects to happen in BSCCO crystals as the structure for both systems are similar; in BSCCO, the superconducting CuO bilayers are well separated by insulating BiO and normal SrO layers. So we were interested to do the similar measurements.
5.2 Data

Fig. 5.1 shows $V_s(T)$ of sample #2 near $T_c$ and 3D model fits by using two sets of $(V_{ab}, V_c)$ data. Fig. 5.2 presents $V_s(T)$ at 12.5mA, 7.5mA, and 5mA and the interlayer vortex coupling model fits for sample #3. Inset displays the temperature dependence of $c$-axis critical current. Fig. 5.3 presents $V_s(T)$ at $I=0.5$mA in an ab-plane magnetic field of 300, 200, 100 and 0G of sample #3. Fig. 5.4 shows the current and field dependence of secondary peak voltage for sample #3. Fig. 5.5 shows the $\rho_c(T)$ and $\rho_{ab}(T)$ derived from $(V_{ab}, V_s)$ and $(V_{ab}, V_c)$ in transition for sample #2. Fig. 5.6 displays a semi-log plot of $V_s(T)$ data and 3D model fit above 86.5K.

5.3 Discussion

We begin with sample #2 and search for coupling evidence at temperatures near the transition. As shown in Fig. 5.1, we find a peak developed near the transition on the secondary layer. The data in solid circles boxes and solid circles are the 3D model analysis to be explained later. The finding lead us to construct the following phenomenological model

$$V_s \propto C \, n_{f}^{2D} \, I_c \, I$$  \hspace{1cm} (5-1)

where $n_{f}^{2D}(T)$ is the density of thermal free vortices on the CuO bilayers, $I_c(T)$ is the $c$-axis critical current density proportional to interlayer Josephson coupling
energy $E_J(T) = \hbar I_c/2e$, $I$ is primary layer current which drives vortices, and $C$ is a fitting parameter.

In this picture, the appearance of the peak is interpreted as a competing effect between the c-axis Josephson coupling and the density of thermal free vortices; the dissipation appears at the onset of the Josephson interaction and disappears at the KT temperature when thermal free vortices are paired.

This picture is supported by the current dependence data in Fig. 5.2. Fig. 5.4 shows the dependence of the peak voltage $V_{\text{peak}}$ (defined as the values of $V_s$ at the top of the peak structure in Fig. 5.2) as a function of sample current. As is evident from eq.(5-1), our vortex model predicts a linear current dependence for the secondary voltage. It is evident from Fig. 5.4 that the data actually follow this linear relation, to within experimental uncertainty (shown as error bars on the data points). It is important to note that this current dependence is linear over a current range in which the measured voltages $V_c$ are highly non-linear, as shown previously in Fig. 4.7. This fact reinforces our belief that correlated flux flow is responsible for the observed peak structure (Recently, Matthew L. Trawick in our Laboratory has obtained comparable data for $V_{\text{peak}}$, which confirms the linear dependence). The suppression of $T_c^c$ and $T_c^{ab}$ at high currents as shown in Table 5.1 is consistent with the predictions of KT theory as described by eq.(1-9). Quantitative analysis further shows excellent agreement between the model and the data; the solid lines produced by the model fall on the data nicely. The c-axis
critical current $I_c(T)$ for the fitting is shown in the inset, and the density of thermal vortices $n_{t^{2D}}(T)$ on CuO bilayers is described in eq.(1-4) and (1-5). We also assumes the mean GL field temperature $T_{co}$ as the c-axis critical temperature $T_c^c$. All the fitting parameters $T_c^c$, $T_c^{ab}$, and $C$ are summarized in Table 5.1.

The behavior of $V_s$ in the ab-plane field also agrees with our model. In Fig. 5.3, we find that $V_s$ decreases when the external field is increased. This reduction is ascribed to the suppression of the interlayer Josephson coupling that has also been observed by Kleiner et al. Quantitatively, $V_s$ shows exponential dependence in $H$ as shown in Fig. 5.4b. We do not observe the modulation of the peak voltage because the highest field (~ 300G) we used is still less than the modulation field of ~ 500G. Our results appear to be consistent with the thermal vortex line theory of Bulaevskii, Ledvij, and Kogan. We find that the connection between our results and BLK’s theory could be that our $T_c^{ab}$ and $T_c^c$ correspond to $T_s$ and $T_{co}$; as $T_c^c - T_c^{ab} \sim 2K$ and $T_{co} - T_s \sim 3K$.

Regardless of the excellence the thermal vortex theory in explaining our experimental results, it was worth reexamining the results under the 3D resistivity model. The mechanism behind this model is that the primary current may be drawn toward the secondary layer giving dissipation in the transition. So a central issue is the degree to which the Laplace’s equation (3D model) accounts for our experimental observations.
Figure 5.1 $V_e$ data at 0.1mA of sample #2 and 3D model fits using two set of $V_{ab}$ and $V_c$ data.
Figure 5.2 $V_s(T)$ of sample #3 at various currents. Inset shows the temperature dependence of the c-axis critical current.
<table>
<thead>
<tr>
<th>I (mA)</th>
<th>$T_c^c$(K)</th>
<th>$T_c^{ab}$(K)</th>
<th>C (Vm²/A²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>87.2</td>
<td>85.7</td>
<td>39</td>
</tr>
<tr>
<td>7.5</td>
<td>87.1</td>
<td>85.6</td>
<td>62</td>
</tr>
<tr>
<td>10</td>
<td>87</td>
<td>85.4</td>
<td>74</td>
</tr>
<tr>
<td>12.5</td>
<td>86.9</td>
<td>85.1</td>
<td>82</td>
</tr>
</tbody>
</table>
Figure 5.3 $V_g(T)$ at 0.5 mA in $H \parallel ab$ of sample #3.
Figure 5.4 Current and field dependence of secondary peak voltage of sample #3.
In discussing the applicability of this model, it is useful to separate the discussion into three regions: (1) the "normal state" region, corresponding to $T > 90K$; (2) a "transition" region which spans the temperature interval 86.6K-90K; and (3) a "non-linear" region, below 86.6K. In regions (1) and (2), the current-voltage characteristics of the sample are linear. Whether or not the 3D model applies depends on whether correlated vortex lines effects can be ignored. Vortex line transport produces a flux flow voltage which leads to a $dA/dt$ term ($A$ is a magnetic vector potential) in the electrical field which is not allow for in the 3D model; note that such flux flow effects also result in linear IV curves. If only "pancake" vortices (i.e., those without long-range correlations along the c-axis) are germane, then their effects would presumably be automatically incorporated into the 3D model; although the motion of pancake vortices also involves flux flow effects, the local nature of these effects would like be apparent as an effective resistivities and thus consistent with the 3D model assumptions.

Region 1 ($T > 90K$): In this region, there is no theoretical reason to suggest that flux flow effects should be important, so that the 3D model should give good results. Fig. 3.2 shows the $\rho_{ab}$ and $\rho_c$ calculated from the measured sample voltages $V_{ab}$, $V_s$, and $V_c$. Because only two of these voltages are required to compute the two resistivity components, the redundancy in the data enable us to check for consistency in our measurements. Accordingly, Fig. 3.2 shows the resistivities computed from the sample voltages paired in different ways: ($V_{ab}$, $V_s$)
and \((V_{ab}, V_c)\). It is clear from this figure that there is a high degree of internal consistency in the measured voltages, since the computed resistivities differ by only \(\sim 5\%\) throughout this temperature range.

Another check on the internal consistency of the data in this range can be seen in Fig. 3.2, which shows the 3D model calculation of the voltage \(V_s\) determined from the voltage pair \((V_{ab}, V_c)\). Comparison of the predicted voltage with the actual measured voltage again shows a high degree of internal consistency; in this case the model and data appear to agree to within \(\sim 10\%\) over the full temperature range.

Region 2- \((86.6K < T < 90K)\): Referring to the temperature region above 86.6K in Fig. 5.5, it is clear that there is a disparity between the 3D model computations of \(\rho_{ab}\) and \(\rho_c\), when these quantities are calculated by two different methods. In the region around 87K, the disparity is \(\sim 30\%\), a reasonable amount, in our opinion, since the resistivities and sample voltages are changing rapidly with temperature. For example, both \(\rho_{ab}\) and \(\rho_c\) changes by nearly a decade in a 2K temperature range, and the measured voltages \(V_{ab}\) and \(V_c\) also shows such a rapid variation in this temperature interval, as indicated in Fig. 3.2. The \(V_s\) data seem to be roughly constant over the upper part of this range (see Fig. 5.6), dropping by about a factor of two between 87K-88K. Using the 3D model and the measured \(V_{ab}\) and \(V_c\) data to "predict" \(V_s(T)\) in this temperature interval leads to good consistency with the data above 88K, but to a significant disparity (a factor of 3-4)
in the region 87K-88K. In this interval, the predicts of the 3D model shows a broad "peak" with what appears to be some poorly resolved interval structure.

Although the existence of this peak, which is at significant variation with the data, tempts one to conclude that the 3D model is breaking down because of vortex lines effects, a more likely explanation is that the peak is a spurious result without physical context. In our judgement, the peak, as well as the general discrepancy between the 3D model and the measured $V_s$ in this temperature range, can be ascribed most plausibly to experimental uncertainty arising from the extremely strong temperature dependence of the voltage data.

Region 3- ($T < 86.6K$): As previously discussed, the IV characteristics of the $V_e(T)$ data in this temperature interval are non-linear. Because the 3D model assumes a linear material, its predictions in this range are not expected to be valid. Nevertheless, in Fig. 5.1, we show the "predicted" values of $V_e$ as solid symbols, along with the measured values of $V_e(T)$ (as open symbols, connected by lines). The predicted values of $V_e(T)$ are determined from the voltage pair $(V_{ab}, V_c)$ for a dc current of 0.1mA, which here lies in the nonlinear region of the current-voltage characteristics. In this range, there are two sets of such voltage pairs, and the predictions of these two sets are shown in Fig. 5.1 as filled boxes and circles, respectively. As in section 3.2, the resistivities (see Fig. 5.5) are determined first and then used to find $V_s$ (see Fig. 5.1). Using the IV characteristics shown in Fig. 4.5 and 4.7, the solid circles were obtained from the
3D model for a dc current of 0.1mA. These IV characteristics were obtained over a period of several days, and for each curve the sample temperature was electrically stabilized to within ~ 50mK.

By contrast, the solid boxes were part of the measured $V_{ab}$ and $V_c$ (see Fig. 3.2) taken at higher temperatures (Region 2, above; note that the 86.6K solid box appears on Fig. 5.1 and 5.6). This voltage pair, $V_{ab}$ and $V_c$, was measured at fixed $I_{ab}$ and $I_c$, respectively, while the sample temperature drifted lower in a continuous manner. It took about 30 minutes for the sample temperature to drift from 90K-85K. The disparity between the predictions of the two data sets (solid circles and solid boxes) is probably the result of a temperature misalignment resulting from the different ways the data were collected. We did not try to measure this temperature misalignment explicitly. However, if one translates the solid circles about 0.4K lower in temperature, then they come in rough alignment with the solid boxes; a 0.4K temperature shift is qualitatively consistent with our general experience on measurements taken under conditions of slowly drifting temperatures.

The actual measured values of $V_s(T)$, shown as open boxes, were taken in a separate data run, with the sample warmed to 90K and then allowed to drift continuously over a thirty minutes period. During this period, the sample current was fixed at 0.1mA and the voltage was sampled at regular intervals. Note that a test run was made in which a limited number of $V_{ab}$ and $V_s$ data point were
measured simultaneously in 85K < T < 90K while the temperature drifted lower. These data were compared with data taken independent temperature-drift runs to verify run-to-run consistency. In other words, we verify that the temperature calibration obtained in temperature-drift runs is consistent among such runs, but that there is a offset (probably about 0.4K) between the temperature of temperature-stabilized runs and temperature-drift runs.

If one compares the 3D model predictions for $V_s$ (solid boxes) with the measured values of $V_s$ (open boxes), the disparity is about 40% in the region where the experimental peak occurs at 86.3K. However, it is evident from Fig.5.6 that the experimental uncertainties in $V_{ab}$ and $V_c$ would translate into an uncertainty in the $V_s$ calculation from the 3D model that is larger than the measured peak in $V_s$. Hence we cannot tell whether or not that peak is found in the 3D anisotropic model.

The disparity is a factor of 10 or more in the same region, when one compares the measured values of $V_s$ with those predicted by measurement of IV characteristics. For neither data set does the 3D model predict a peak near that actually measured at 86.3K. The 3D model does predict an apparent peak at about 87.3K for the data set represented by the closed boxes. However, since this data set and the measured $V_s$ were both obtained during temperature drift runs, and since, as noted above, temperature measurements are consistent between such runs, there is little chance that this peak corresponds to that actually measured a
Figure 5.5 Ab-plane and c-axis resistivities of sample #2 derived from the 3D resistivity model.
Figure 5.6 Temperature dependence of $V_s$ and 3D model fit at 0.1mA near transition of sample #2.
full degree lower. In summary, we find no evidence suggesting that the 3D model produces a peak in the temperature range at which we actually measure a peak in $V_s$. We cannot rule out that a more sophisticated version of the 3D model, which correctly allows for the non-linearity of the medium, might be more successful. However, since no such model has yet been formulated, any speculation about the possible success or failure of such model would clearly be premature (Note that very recent measurements by Matthew L. Trawick in our laboratory on a slightly different sample configuration, and using significantly improved fabrication procedures, showed that the existence of a very large peak (about a factor of 50 greater than the background voltage) in the measurement of $V_s$. The amplitude of this peak increased linearly with sample current, and in nearly all respects appears consistent with our data and also with our vortex model interpretation, as discussed in this chapter.).

As noted earlier, the 3D model cannot be meaningfully applied for temperatures less than about 88K. Therefore, the current dependence of the secondary peak voltage in Fig. 5.4a cannot be examined within the model. This is also true for the magnetic field dependence of the peak voltage at temperatures below 88K.

5.4 Conclusion

In conclusion, we observed pronounced voltage peaks on secondary layers
of BSCCO crystals near transition in the transport measurements by using a dc flux-transformer geometry. Our analysis of voltage data showed that because of experimental uncertainties, the classical 3D anisotropic linear resistivity model cannot be used either to explain the voltage peak observed on the secondary layer in transition, or the dynamics of the peak in increasing current and magnetic field. A model based on the interlayer Josephson coupling of thermal vortices was proposed to account for the data very well.
CHAPTER VI

VORTEX PHASES NEAR TRANSITION TEMPERATURE

6.1 Introduction

In this chapter, we address the issue of vortex dynamics and vortex states in BSCCO with a magnetic field applied parallel to the c-axis. Most of the results shown in this chapter have been published in Ref. [79].

6.2 Data

Fig. 6.1 shows the $V_{ab}(H)$ at $I=0.5mA$ at five temperatures near $T_c$ of sample #4. Fig. 6.2 displays $V_{ab}(I)$ at temperatures near $T_c$ of sample #2. Fig. 6.3 shows $V_s(H)$ near $T_c$ at 0.5mA of sample #5. Fig. 6.4 presents $V_s(T)$ in fields 40, 20, 10 and 0 G of sample #5. Fig. 6.5 displays $V_s(H)$ at 6, 4, 2, 1 and 0 mA of sample #6. Fig. 6.6 shows the current dependence of melting field and secondary peak voltage. Fig. 6.7 presents a vortex phase diagram of sample #5. Fig. 6.8 displays the temperature dependence of the peak voltage at vortex melting.

6.3 Discussion

We first search evidence for the magnetic penetration field. In Fig. 6.1 for
sample #4, we find that in the superconducting state of $T = 85.6K$ the magnetic field dependence of $V_{ab}$ shows flux flow dissipation at field above $\sim 1G$ denoted as $H_p$. Below $H_p$, $V_{ab}$ is zero, signifying that the sample is in the Meissner state. As expected, the penetration field $H_p$ is enhanced when the sample temperature is lowered. We recorded $H_p$ for each temperature and plotted in the inset of Fig. 6.1. It is clear that the sample becomes diamagnetic at $85.7K$, denoted as $T_m$.

The above finding led us to examine the interrelation between the onset of diamagnetism and the superconducting transitions in this sample. From the IVs in Fig. 6.2 and the power law analysis, we find that $T_m = 85.7K$ is between $T_c^{ab} \sim 85.5K$ and $T_{co} \sim 85.9K$ implying the Meissner current in BSCCO is not yet fully developed at the upper transition temperature.

In addition to the penetration field, another critical field $H_m$ at a higher value was found from the same measurements on the secondary layer. In Fig. 6.3, one can see that the secondary voltage $V_s$ shows a non-monontonic peak at low temperatures. This peak allows us to identify $H_p$ and $H_m$. For example at $87.7K$ (see figure in the inset), $H_p$ is at $\sim 7G$ and $H_m$ is $\sim 24G$. When the sample temperature is increased, both $H_p$ and $H_m$ decreased and meet together to zero at $88.1K$.

We discuss the physical meaning of $H_m$ in terms of the dynamics of 2D vortex pancakes on CuO bilayers in the following. We believe that the decrease of $V_s$ at a higher field is a consequence of the reduction of the interlayer coupling
strength of 2D vortices. According to the theory of vortex lattice melting [46], this reduction becomes effective when 2D vortices overlap each other. Using eq.(1-16), the vortex spacing $d$ at $T = 87K$ is at $\sim 1\mu m$, while the size of vortices $\lambda$ is estimated to be $\sim 1.5\mu m$ from the two-fluid model [65]. $\lambda = \lambda_o (1-T/T_c)^{-1/2}$, $\lambda_o \sim 1500\AA$ (Cooper et al. [11]) is the ab-plane penetration depth at $T=0$ and $T_c \sim 88.4K$. So the condition of melting $d \sim \lambda$ is satisfied. Moreover, thermal fluctuations enhance the melting effect as we found that the lateral thermal displacement of each vortex is $\approx 0.5\mu m$ which is estimated from eq.(1-11) with $T=87K$, $H_p \approx 30G$ and $L=20\mu m$. We therefore conclude that $H_m$ is a melting field. At this field, we believe, what physically happens is that a three dimensional vortex line (3DVL) state melts into a weakly interacting two dimensional vortices or liquid (2DVL) state.

Consistent experimental results with Fig. 6.3 were also observed in Fig. 6.4 where $V_s(T)$ was measured in several fixed fields. As a verification of the equivalence, in the inset, we find that $T_m$ at 88.1K determined from $V_s(H)$ is also the peak temperature of $V_s(T)$ which lies between $T_c^{ab} \sim 87.8K$ and $T_c^c \sim 88.4K$. The larger margin $\sim 0.4K$ between $T_c^{ab}$ and $T_m$ found from $V_s(H)$ as compared to 0.2K from $V_{ab}(H)$ is believed to be due to a higher sensitivity on the secondary layer.

The changing of the primary current shows interesting effects on the
Figure 6.1 $H (|| c)$ dependence of $V_{ab}$ at 0.5 mA of sample #4. Inset shows $T$ dependence of penetration field.
Figure 6.2 Current-voltage characteristics on the primary layer of sample #4.

Inset displays temperature dependence of a(T).
Figure 6.3 $H \parallel \ell$ dependence of $V_s$ at 0.5mA near $T_c$ of sample #5.
Figure 6.4 Temperature dependence of $V_s$ in $H (\parallel c)$ of sample #5 at 0.5mA.
coupling of 2D vortices. In Fig. 6.5, we find that the amplitude of \( V_s(H) \) increases as the current is increased and the peak voltage shows a linear dependence (see Fig. 6.6b). While these features are as expected based on our coupling model, both \( H_p \) and \( H_m \) reduce as the current is increased (in Fig. 6.6a). We believe that these phenomena results from the reduction of the interlayer coupling when more free vortices are created by current (according to the KT theory) and the reduction by the self induced field of current.

6.4 Vortex phase diagram

By marking \( H_p \) and \( H_m \) for each temperature at a low current of sample #5, we mapped out a vortex phase diagram in Fig. 6.7. We like to point out an unique feature in this phase diagram. That is \( H_p(T) \) and \( H_m \) lines, although, are found to be similar to \( H_p(T) \) and \( H_{irr}(T) \) of Brawner et al., we do not observe the "reentrant" behavior. \( H_m(T) \) line shows a concave-down curve at temperatures below 88.1K and so does \( H_p(T) \) line at temperatures below 87.7K (above it turns into a convex tail). The data of \( H_p \) and \( H_m \) at temperatures below \( \sim 87K \) were not available as the lower temperature \( V_s \) signal is beyond our voltage resolution (see Fig. 6.8).

The diamagnetism, or finite \( H_p \), above \( T_c^{ab} \) in the sample is attributed to the effects of finite sample size. Using eq.(1-7), we estimated the depairing current \( I_w \sim 10^{-6}A \) for a single CuO bilayer at \( T=87.5K \) with \( W \sim 0.5mm \). This value gives
Figure 6.5 $V_s$ in $H(\parallel c)$ for several currents at $T=85.3K(< T_c^{ab})$ of sample #6.
Figure 6.6 Current dependence of peak voltage $V_p$ and melting field $H_m$ of sample #6.
Figure 6.7 Vortex phase diagram near the transition of sample #5.
Figure 6.8 Secondary voltage $V_m(T)$ at melting field for sample #5. The solid line is an exponential fit.
$I_w \sim 10\text{mA}$ for a total of $\sim 10^4$ bilayers in the sample if we naively assume the overall $I_w$ is a sum of each bilayer depairing current. Given the current and eq.(1-10), we roughly estimate $H_p$ near $T_c$. At $87.5\text{K}$, with $W \sim 0.5\text{mm}$, $\xi \sim 10^3\text{Å}$, $H_{c1} \sim 10^3\text{G}$, and $N \sim 2\times10^4$, we find $H_p \sim NH_{c1} \sim 20\text{G}$, which is not far from the data of $10\text{G}$. This agreement provides another evidence for a coherent quantum effect in BSCCO by interlayer Josephson coupling.

Finally, we briefly comment on the difference between $H_p$ and $H_{c1}$. According to Bean and Livingston (BL) [66] theory, a surface vortex barrier will be created in a superconductor near $H_{c1}$ line. It is caused by the electromagnetic interaction between external field and the magnetic-induction of the superconductor. This barrier will trap or delay vortices from leaving or entering the superconductor. Because of the surface barrier, an external field has to be slightly higher than $H_{c1}$, reaching $H_p$, to push more vortices into the superconductor. The quantification for the barrier of a specific sample is difficult since it is morphology dependent; however, it is believed to be small.

6.5 Conclusion

We studied the interlayer interaction of 2D vortices in BSCCO crystals near the superconducting transition. We found evidence for vortex first penetration. In the mixed state, 2D vortices interact strongly as 3D vortex lines in low fields and low temperatures, while interact weakly at high fields and high temperatures.
CHAPTER VII

MAKING BSCCO THIN FILMS USING RF SPUTTERING

This chapter summarized my earlier two years work on BSCCO thin film fabrication before I started research on crystals.

7.1 Introduction

Almost in no time after the discovery of high temperature superconductivity in BSCCO compounds by several groups [67-71], Koinuma et al. [72] made superconducting films on YSZ (Yttria-stabilized-zirconia) substrates. There are couple things worth mention in this very early paper. (1) A single oxide target was used. (2) The films were deposited in an atmosphere of mixed O₂/Ar using a low frequency (50Hz) sputtering system. (3) The as deposited brown-colored films were amorphous and insulating. (4) These films became superconducting after postannealing at 800-850°C in oxygen. (5) The superconducting transition was broad with onset at 115K and 92K and a zero resistance state was at ~ 70K.

Later on, epitaxial films in which the CuO plane is parallel to substrate surfaces were made (Fukumoti et al. [73]) by using a magnetron sputtering in cooperation with the technique of in-situ; maintaining a high substrate
temperature, ~ 700C in deposition. These in-situ films showed an improvement in transition temperature $T_c$ up to ~ 96K after postannealing at 875-880C in oxygen for a half hour. This improvement was attributed (Levinson, Shah, and Naito [74]) to atomic reordering during deposition.

The chemical concentrations on the deposited films were found to be different from the oxide targets in a study by Yeh and Hong [75] using Rutherford backscattering (RBS) and scanning electron microscope (SEM). They found that Bi and Cu were rich. This study led to many researches of adjusting target composition to make stoichiometry films.

MgO (100) and SrTiO$_3$ (100) substrates were found to be good substrates for growing oxides films. For example, Habermeier, Sommer, and Mertens et al. [76] and Anaso et al. [77] had successfully grown superconducting films on these substrates. Their films showed the superconducting transition at 85K and a narrow width ~ 5K.

The orientation of substrate in deposition was reported by Eom et al. [78] to be an important factor to film quality. Their substrates were placed off the center line of targets to avoid direct atomic bombardment from the incoming beams. They claimed that this skill could ensure a good control of concentration, and keep substrate temperature low to yield a high deposition rate.

As motivated by these previous works, we attempted to make BiSrCaCuO films using RF diode sputtering.
7.2 RF diode sputtering system, composite targets and film deposition

**AC sputtering mechanism**

The mechanism of an AC sputtering system is that as an alternating electrical field is applied to a chamber of Ar gas between a cathode and an anode, the neutral Ar gas is ionized into plasma consisting of Ar$^+$ and e$. In a half AC cycle, Ar$^+$ ions are driven toward the cathode and bombard the target on it, while in the other half cycle, e$^-$ is driven to targets and neutralized Ar$^+$ gas accumulated on the cathode. By this way, an insulating target can be sputtered.

The parameters to specify a sputtering system are sputtering and deposition rates. The sputtering rate defines the number of atoms sputtered from the target in unit of time which is a function of target size, target density, vacuum pressure and sputtering power. Larger target size, higher pressure and higher power give a higher sputtering rate. The deposition rate specifies the number of the atoms deposited on the substrates. It is a function of the sputtering rate, vacuum pressure, target-substrate distance, substrate orientation, and substrate temperature. Higher sputtering rate, lower pressure, shorter target-substance and lower temperature would give a higher deposition rate.

**Sputtering system**

Fig. 7.1 shows the configuration of our RF (operated at ~15MHz)
sputtering machine (Randex 2400-6J). In this system we had a vacuum chamber with a 5" disk cathode and a 5" anode at a distance of 3". Substrates were placed on the anode (the bottom one). Our substrate surfaces were tilted 45 to 90 degrees off the center line between the cathode and anode. Substrate temperature was controlled by using a K type thermo-couple gauge with a stainless-steel heater amounted directly in contact with the substrates, which was a 300W resistive tube. The substrate temperature range was from room temperature to 700°C with stability ±10°C.

**Composite targets**

We adopted the recipe of Koinuma *et al.* [76] to fabricate oxide targets. The fabrication procedures are; (1) Mixing proper amount of oxide powders. (2) Grinding, and crunching the powders into micro size fine particles. (3) Calcination and crystallization of the oxides by firing the powders at 860-840°C for 15 hours. (4) Repeat steps (2) and (3) twice. The step (4) is to ensure complete reaction and calcination of the powder.

The calcinated powders were then loaded in a 3" dye and pressured into a disk 3mm thick. To avoid cracking the disk, the pressure was ramped slowly to ~20 tons in 10 minutes. The ultimate pressure ~ 1.5 ton/cm² gives 90-95% target density. Target hardening was achieved by annealing targets at 840°C for 3h. High density is very important to keep targets from outgassing in vacuum.
Deposition procedures

Followings are the procedures for operating our RF system.

(1) Load targets, substrates, and the substrate heater into the chamber at atmosphere.

(2) Pump the chamber to $10^{-7}$ Torr using roughing pump and cryogenic Helium pump. Maintain the high vacuum for more than 15 hours.

(3) Close the high vacuum valve and open absorption pump for deposition.

(4) Set substrate temperature by turning on the heater.

(5) Set the vacuum pressure to 20-30 mTorr by feeding argon (and oxygen) gases into the chamber.

(6) Set the sputtering power at 100-150 Watts.

(7) Cleaning targets by presputtering for 3-5 minutes with substrate shutter closed (blocking substrates).

(8) Open substrate shutter and deposit for 1-2h.

(9) *In situ* annealed films in oxygen atmosphere (at 50m torr) for 10 hours if necessary.

(10) Cool substrates to room temperature and remove them from the chamber.
Table 7.1 Summary of parameters for thin film samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Target BiSrCaCu</th>
<th>Substrate</th>
<th>Substrate Temperature</th>
<th>Annealing Temperature</th>
<th>$T_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2:2:2:3</td>
<td>SrTiO$_3$</td>
<td>25°C</td>
<td>860°C</td>
<td>75K</td>
</tr>
<tr>
<td>B</td>
<td>2:1:1.4:1.7</td>
<td>MgO</td>
<td>25°C</td>
<td>860°C</td>
<td>70K</td>
</tr>
<tr>
<td>C</td>
<td>3:2:1:2</td>
<td>MgO</td>
<td>670°C</td>
<td>880°C</td>
<td>85K</td>
</tr>
</tbody>
</table>
Figure 7.1 Configuration of RF sputtering system.
We characterized our 1-2μm films using resistance $R(T)$ measurements, magnetic susceptibility $\chi(T)$, scanning electron microscopy, and Rutherford backscattering analysis (RBS). The RBS analysis was done in the Ohio State Van de Graaff accelerator using Alpha particles.

7.3 Data

We intend to show results from three representative samples. Table 7.1 summarize some parameters of these films which includes target composition, substrate kind, substrate temperature in deposition, postannealing temperature, and zero resistance temperature. Fig. 7.2 shows the susceptibility $\chi(T)$ and resistance $R(T)$ of film A at 1mA, deposited from the A target. Fig. 7.3 shows the $R(T)$ of film B at 1mA, made from the B target. Fig. 7.4 shows the $R(T)$ of film C at 1mA, deposited in-situ at 670C from the stoichiometric C target.

7.4 Discussion

Film A (Fig. 7.2) shows the onset of superconductivity at $\sim 90K$ as indicated by a sharp decrease in $R(T)$ after 10 hours postannealing. In spite of the high onset temperature, the zero resistance temperature $T_c(R=0)$ is at $\sim 74K$. At that temperature, $\chi(T)$ also shows a clear step indicating onset of Meissner screening current or diamagnetism. Above $T_c$, however, the broad resistive transition implies the film composition is inhomogeneous.
Figure 7.2 Temperature dependence of the magnetic susceptibility and resistance of film A. This film was annealed for 10 hours at 860°C.
Figure 7.3 Temperature dependence of the normal state resistance of film B.
Figure 7.4 $R(T)$ of film C. This film was first annealed at 880°C for 5 hours (□) and then for another 10 hours (■) at the same temperature.
Film B (Fig. 7.3) shows a similar broad transition at 82K and 108K indicating multiple phases. RBS analysis indicated the film composition 1.7-2-1-2.5 in shortage of Bi and richness in Cu as compared to 2212. This off-stoichiometry is believed to cause the observed multiple phases.

To adjust Bi and Cu concentrations, we then fabricated the film C from target C (3-2-1-2) in situ at a substrate temperature of 670C. As illustrated in Fig 7.4, this film (after 5 hours postannealing) shows a clear superconducting transition at ~ 85K without a secondary phase at 110K. RBS analysis indicated that the film composition was close to 2212 within an uncertainty of 5%. Another 10 hours annealing at the same temperature clearly reduces the normal state resistance and the extrapolated zero temperature resistance although $T_c$ is not increased. This low zero temperature resistance reminiscences the resistivity of the single crystal sample #1 seen in chapter II signifying an improvement in film quality.

7.5 Conclusion

We made 85K superconducting $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}$ films by using a RF diode sputtering system. We found that the stoichiometry in films was a key factor in order to achieve single phase films. In situ deposition and post annealing were found to be necessary to raise the transition temperature.
APPENDICES

A-BASIC Program

' THIS PROGRAM IS FOR AVERAGING MULTIPLE RESISTANCE DATA '

' FOR GIVEN TEMPERATURE '

CLS

DIM TEM(512), T(512), SAMET(512)
DIM RES(512), R(512), AVR(512)
DIM NUM(512)

' INPUT THE NAME OF THE DISK DRIVE '

' INPUT TEMPERATURE DATA FILES '

PRINT

PRINT "Input the name of temperature data file"

INPUT ; TEMP$

OPEN "C:\WAN\" + TEMP$ + ".DAT" FOR INPUT AS #1

10 IF EOF(1) THEN 20

N% = N% + 1

INPUT #1, X#

TEM(N%) = X#
GOTO 10

20   CLOSE 1
N%   = 0

' INPUT RESISTANCE DATA FILE '  
PRINT
PRINT "Input the name of the resistance data file"
PRINT ;
INPUT ; RESIS$
PRINT
PRINT "WAITING......."
OPEN "C:\WAN\" + RESIS$ + ".DAT" FOR INPUT AS #2

30   IF EOF(2) THEN 40
N%   = N% + 1
INPUT #2, X#
RES(N%) = X#
DATAN% = N%
GOTO 30

40   CLOSE 2

' ARRANGE RESISTANCE POINTS IN A DECREASING MODE FOR A T 
, 
60   FOR J% = 1 TO DATAN% - 1
FOR N% = J% + 1 TO DATAN%
IF TEM(N%) <= TEM(J%) THEN GOTO 90
H# = TEM(N%)
TEM(N%) = TEM(J%)
TEM(J%) = H#
P# = RES(N%)
RES(N%) = RES(J%)
RES(J%) = P#
90 NEXT N%
NEXT J%

' CALCULATE THE NUMBER OF RESISTANCE POINTS OF A T AND '
' AVERAGING RESISTANCE '
OPEN "C:\WAN" + "M" + TEMPS + ".DAT" FOR OUTPUT AS #1
CLOSE #1
OPEN "C:\WAN" + "M" + RESISS + ".DAT" FOR OUTPUT AS #2
CLOSE #2
101 M% = 1
L% = 1
N% = 1
104 IF TEM(N% + 1) <> TEM(N%) THEN GOTO 105
IF N% >= 511 GOTO 120
L% = L% + 1

105 SUM# = SUM# + RES(N%)

IF TEM(N%) = TEM(N% + 1) GOTO 110

AVR(M%) = SUM# / L%

OPEN "C:\WAN\" + "M" + TEMPS + ".DAT" FOR APPEND AS #1

WRITE #1, TEM(N%)

CLOSE #1

OPEN "C:\WAN\" + "M" + RESISS + ".DAT" FOR APPEND AS #2

WRITE #2, AVR(M%)

CLOSE #2

SAMET(N%) = L%

SUM# = 0

M% = M% + 1

L% = 1

110 N% = N% + 1

GOTO 104

120 END
B-Derivation of 3D anisotropic resistivity model

In this section, we give a detailed derivation of static electrical potential $V(x,y,z)$ in terms of resistivities $\rho_{ab}$ and $\rho_c$ of anisotropic materials. The explicit relationships between the resistivities and the quantities $V_{ab}$, $V_x$ and $V_c$ measured on our BSCCO crystals using six electrodes will also be presented.

We begin with solving the 3D Laplace equation

$$\nabla \cdot J = \frac{1}{\rho_{ab}} \frac{\partial^2 V}{\partial x^2} + \frac{1}{\rho_{ab}} \frac{\partial^2 V}{\partial y^2} + \frac{1}{\rho_c} \frac{\partial^2 V}{\partial z^2} = 0 \quad (A-1)$$

where $\rho_{ab}$ and $\rho_c$ are the ab-plane and c-axis resistivity respectively. For the ab-plane measurements (see Fig. 2.6a), we construct a Fourier series solution below

$$V = \sum V_{nm} \sin\left[\frac{n\pi x}{L}\right] \cos\left[\frac{m\pi y}{W}\right] \cosh\left(\frac{\rho_c}{\rho_{ab}}\sqrt{\frac{n^2}{L^2} + \frac{m^2}{W^2}}\right) \quad (A-2)$$

where $m \geq 0$ and $n$ is an odd positive integer, and $L$ and $W$ are sample length and width. This simplified solution is obtained by placing the origin of a cartesian coordinate at the center of the bottom surface as shown in Fig. A.1a. The sizes of contacts are either $L/4 \times W/4$ or $L/4 \times W$. This solution meets the requirement of zero normal current at boundaries of $x = \pm L/2$, $y = 0$, $W$ and $z = 0$.

We determine $V_{nm}$ in eq. (A-2) by the following integral equation,

$$\int \int J_z(z=D) \sin\left(\frac{n\pi x}{L}\right) \cos\left(\frac{m\pi y}{W}\right) \, dx \, dy = \frac{\mu_0}{\mu_2} \int_0^W \sin\left(\frac{n\pi x}{L}\right) \, dx \int_0^D \cos\left(\frac{m\pi y}{W}\right) \frac{1}{\rho_c} \frac{\partial V}{\partial z} \bigg|_{z=D} \quad (A-3)$$
Figure A.1 (a) Cartesian coordinate for the ab-plane measurements and (b) for the c-axis measurements.
with

\[ J_{z}(z=D) = -\frac{1}{\rho_c} \left. \frac{\partial \phi}{\partial z} \right|_{z=D} \quad (A-4) \]

On the left side of eq.(A-3) we assume that \( J_{z}(z=D) = 16I/LW \), denoted as \( J_{\omega} \), is uniform on the area of the current contact and zero elsewhere where \( I \) is the total applied current. On the right hand side of the equation the orthogonal properties of sine and cosine functions over the entire surface gives

\[
V_{n0} = \frac{16I K \cos(\frac{n\pi}{4})}{W n^2 \pi^2 \sinh[\frac{\rho \pi D}{L}]} \quad (A-5)
\]

\[
V_{nm} = \frac{128I K \cos(\frac{n\pi}{4}) \sin(\frac{m\pi}{4})}{nmLW \pi^3 [((\frac{n}{L})^2 + (\frac{m}{W})^2)^{1/2} \sinh(p \pi [(\frac{n}{L})^2 + (\frac{m}{W})^2]^{1/2} D)]} \quad (A-6)
\]

with \( k = (\rho_c \rho_{ab})^{1/2} \) and \( p = (\rho_c / \rho_{ab})^{1/2} \).

By plotting out the following normalized current density

\[
\frac{J_{z}(z=D)}{16I/LW} = \sum_{n=1} \left[ \frac{\cos(\frac{n\pi}{4}) \sin(\frac{n\pi x}{L})}{n \pi} + \sum_{m=1} \frac{8 \cos(\frac{n\pi}{4}) \sin(\frac{m\pi}{4}) \sin(\frac{n\pi x}{L}) \cos(\frac{m\pi y}{W})}{nm \pi^2} \right]
\]

(A-7)

over the top surface using a Mathcad program, we can check eq.(A-5), eq.(A-6)
Figure A.2 $J_\perp(x,y)/J_\perp$ and $V_{ab}(x,y)/V_\perp$ on the top layer of BSCCO crystals for the ab-plane measurements.
and the program. Fig. A.2 shows a 2D surface plot for the left half of sample \#2 with \( n \) and \( m \) up to 30. In this figure, one can see that \( J_z / J_0 \) is -1 on the current contacts and zero elsewhere. The minus sign is because of the direction of current injection. The potential difference between the voltage electrodes at \((x,y,z=D)\) and \((-x,y,z=D)\) is

\[
V_{ab}(x,y) = \frac{32I_k}{W} \sum_{n=1}^{n=30} \frac{\cos\left(\frac{n\pi}{4}\right)\sin\left(\frac{n\pi x}{L}\right)}{n^2\pi^2\tanh(p\pi nD/L)}
\]

\[
\frac{256I_k}{W} \sum_{n,m=1}^{n=30,m=30} \frac{\cos\left(\frac{n\pi}{4}\right)\sin\left(\frac{n\pi x}{L}\right)\sin\left(\frac{m\pi}{4}\right)\cos\left(\frac{m\pi y}{W}\right)}{mn\pi^2[n^2+(\frac{mL}{W})^2]^{1/2}\tanh(p\pi n^2+(\frac{mL}{W})^2)^{1/2}\frac{D}{L}}
\]

where \( V_{ab}(x,y) = 2V(x,y,z=D) \). To study the potential distribution on the top layer, again we normalized \( V_{ab}(x,y) \) to the prefactor \( 16I_p c D/LW \), denoted as \( V_o \) in unit of Volts. In contrast to \( J_z / J_0 \), \( V_{ab} / V_o \) in Fig. A.2b exhibits a smooth feature near the current contacts. The parameters for the simulation are \( L=0.9\)mm, \( W=0.6\)mm, \( I=0.1\)mA, \( D=6\)\mu m, \( \rho_c = 5\)\Omega cm and \( \rho_{ab} = 200\)\mu \Omega cm. The voltage measured on the secondary layer between the voltage electrodes at \((x,y,z=0)\) and \((-x,y,z=0)\) is

\[
V_s(x,y) = \frac{32I_k}{W} \sum_{n=1}^{n=30} \frac{\cos\left(\frac{n\pi}{4}\right)\sin\left(\frac{n\pi x}{L}\right)}{n^2\pi^2\sinh(p\pi nD/L)}
\]
Now, we will explore the potential for the c-axis measurements where current is applied along the c-axis. First, we move the origin of the coordinate from the center to the edge as illustrated in Fig. A.1b for the purpose of symmetry. Second, to simplify our calculation, we modified the size of voltage contacts on the bottom layer from L/4 x W to L/4 x W/4. Under these modifications, we can write down another Fourier solution,

\[
V = \sum A_{nm} \cos\left(\frac{n\pi x}{L}\right) \cos\left(\frac{m\pi y}{W}\right) \cosh\left(\frac{\rho_c}{\rho_{ab}}\right)^{\sqrt{n^2 + \left(\frac{mL}{W}\right)^2}} + \sum B_{nm} \cos\left(\frac{n\pi x}{L}\right) \cos\left(\frac{m\pi y}{W}\right) \sinh\left(\frac{\rho_c}{\rho_{ab}}\right)^{\sqrt{n^2 + \left(\frac{mL}{W}\right)^2}} + C_Z
\]

(A-10)

where \(n\) and \(m\) are integers \(\geq 0\). The second and third terms in eq.(A-10) are to meet the boundary conditions at both top and bottom layers. By applying eq.(A-3) on the top layer, we find for \(m=n=0\),

\[
C = \frac{\rho_c I}{LW}
\]

(A-11)

For \(m=0\),

\[
\frac{256 I k}{W} \sum_{n,m=1} \frac{\cos\left(\frac{n\pi}{4}\right) \sin\left(\frac{n\pi x}{L}\right) \sin\left(\frac{m\pi x}{4}\right) \cos\left(\frac{m\pi y}{W}\right)}{n^2 + \left(\frac{mL}{W}\right)^2} \sinh\left(\rho x\right) \sin\left(\frac{n\pi x}{2} + \left(\frac{mL}{2W}\right)^2\right)^2 \frac{D}{L}
\]
\[ B_{n0} = \frac{8kI\sin\left(\frac{n\pi}{4}\right)}{n^2\pi^2 W} \] (A-12)

For \( n = 0 \),

\[ B_{0m} = \frac{8kI\sin\left(\frac{m\pi}{4}\right)}{m^2\pi^2 L} \] (A-13)

For \( n \) and \( m > 0 \),

\[ B_{nm} = \frac{64kI\sin\left(\frac{n\pi}{4}\right)\sin\left(\frac{m\pi}{4}\right)}{nmLW\pi^3\left[ \left(\frac{n}{L}\right)^2 + \left(\frac{m}{W}\right)^2 \right] \nu^2} \] (A-14)

By applying eq.(A-3) on the bottom layer with all known \( B \) coefficients, we have

\[ A_{n0} = \frac{-8kI\sin\left(\frac{n\pi}{4}\right) \cosh\left[ \frac{p n \pi D}{L} \right] - 1}{n^2\pi^2 W} \left\{ \frac{2}{\sinh\left[ \frac{p n \pi D}{L} \right]} \right\} \] (A-15)

\[ A_{0m} = \frac{-8kI\sin\left(\frac{m\pi}{4}\right) \cosh\left[ \frac{p m \pi D}{W} \right] - 1}{n^2\pi^2 L} \left\{ \frac{2}{\sinh\left[ \frac{p m \pi D}{W} \right]} \right\} \] (A-16)
\[ A_{mn} = -\frac{64k I \sin\left(\frac{m\pi}{4}\right) \sin\left(\frac{n\pi}{4}\right) \cos\left(\frac{m\pi y}{L}\right) \cos\left(\frac{n\pi x}{W}\right) \cosh\left(\frac{p\pi \left[\left(\frac{n}{L}\right)^2 + \left(\frac{m}{W}\right)^2\right]^{1/2}}{L}\right) - 1}{n m \pi^3 L W \left[(n/L)^2 + (m/W)^2\right]^{1/2} \sinh\left(\frac{p\pi \left[\left(\frac{n}{L}\right)^2 + \left(\frac{m}{W}\right)^2\right]^{1/2}}{L}\right)} \]

\( \text{(A-17)} \)

We find \( J_z(x,y)/J_0 \) at the top and the bottom surfaces is

\[ \sum_{m=1}^{\infty} \frac{\sin\left(\frac{m\pi}{4}\right) \cos\left(\frac{m\pi y}{W}\right)}{2m\pi} + \sum_{n=1}^{\infty} \frac{\sin\left(\frac{n\pi}{4}\right) \cos\left(\frac{n\pi x}{L}\right)}{2n\pi} \]

\[ + \sum_{n,m=1}^{\infty} \frac{4\sin\left(\frac{m\pi}{4}\right) \sin\left(\frac{n\pi}{4}\right) \cos\left(\frac{n\pi x}{L}\right) \cos\left(\frac{m\pi y}{W}\right)}{n m \pi^2} + \frac{1}{16} \quad \text{(A-18)} \]

Again, we plot \( J_z(x,y)/J_0 \) in Fig. A.3a for the whole sample with \( n \) and \( m = 30 \).

The similarity of this Figure to Fig. A.2a verifies this program and our derivations.

We also calculate the potential difference between voltage contacts at \((x,y,z=D)\) and \((x,y,z=0)\),

\[ V_c(x,y) = \sum_{m=1}^{\infty} \frac{16k I \sin\left(\frac{m\pi}{4}\right) \cos\left(\frac{m\pi y}{W}\right) \cosh\left[\frac{pm\pi D}{W}\right] - 1}{m^2\pi^2 L} \left[\frac{\sinh\left[\frac{pm\pi D}{W}\right]}{\frac{pm\pi D}{W}}\right] \]

\[ + \sum_{n=1}^{\infty} \frac{16k I \sin\left(\frac{n\pi}{4}\right) \cos\left(\frac{n\pi x}{L}\right) \cosh\left[\frac{pn\pi D}{L}\right] - 1}{n^2\pi^2 W} \left[\frac{\sinh\left[\frac{pn\pi D}{L}\right]}{\frac{pn\pi D}{L}}\right] + \frac{\rho_c l D}{L W} + \]

\[ \text{(A-19)} \]
To test the above equation and its Mathcad program, we calculated $V_c(x,y)/V_o$ by using the same parameters for $V_{ab}/V_o$. As shown in Fig. A.3b, it is clear that this program works properly.

The potential distribution in the sample for the ab-plane measurement is basically characterized by eq.(A-2). At any depth in $z$ the pattern is a reproduction of the profile at the primary layer but the amplitude decays exponentially with a characteristic length $z_i = [(\rho_c/\rho_{ab})(1/L^2 + 1/W^2)]^{-1/2}$ (see eq.(A-2) with $n = m = 1$). For sample #2, $z_i$ is estimated to be $2 \mu m$ which is about one tenth of the sample thickness. For the c-axis measurement, the pattern is more complicated as described by eq.(A-10). Still it is obvious that the potential is not homogeneous over the top and bottom surfaces (see Fig. A-3b) and the current density between current contacts is much higher than that between the voltage contacts, implying nonuniform current distribution.
Figure A.3 \( \frac{J_z(x,y)}{J_0} \) and \( \frac{V_c(x,y)}{V_o} \) on the top layer for the c-axis measurements.
REFERENCES


