Modeling of Temperature Dependent Current-Voltage Curves of YBCO/Ag Composites

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Abstract—We have measured the current-voltage (I-V) characteristics of thin film composites made from YBa2Cu3O7-x (YBCO) and Ag. When deposited upon a substrate, this material appears to form arrays of superconducting-normal-superconducting (SNS) junctions. To make these measurements, the films were patterned into microbridges and immersed directly into the cryogen to provide a constant temperature environment and to avoid problems of local heating. The data were fitted by several phenomenological models in an effort to understand the dissipation mechanisms appropriate to these materials.

I. INTRODUCTION

Devices that utilize the motion of vortices have been under study for some time. Since materials used to fabricate these devices strongly affect vortex motion and hence the operation of the device itself, attempts have been made to discover or produce materials with properties that are conducive to vortex motion. Inhomogeneous composites consisting of a superconductor and a non-superconductor in intimate contact are likely candidate materials since superconductivity in the composite material will be weaker than in the pure material. Initial investigations in this study focused upon co-sputtered films of LaAlO3 and YBCO [1], [2]. Subsequently, interest shifted from these materials to a series of noble metal matrix composites [3], [4].

Several phenomenological models have been proposed to describe the dissipation observed during vortex motion in superconducting materials. These include the thermally activated flux flow (TAFF) model [5] [6], the vortex glass (VG) model[7] [8], and the modified Ambegaokar-Halperin (MAH) model [9], [10]. For purposes of this paper, we examined these models and made fits to our data.

II. SAMPLE PREPARATION AND CHARACTERIZATION

Noble metal matrix composites are formed by room temperature evaporation of Au or Ag onto (100)-oriented MgO, SrTiO3, or LaAlO3 substrates. The substrates with the metal films were then mounted on a substrate holder for the YBCO deposition. YBCO was deposited on the Au films using inverted cylindrical magnetron sputtering with the substrate heated to 800° C [11], and on the Ag films using off-axis sputtering with the substrate heated to 680° C. At these temperatures, the metal films coalesced into islands on the substrate and the YBCO filled the space in between. SEM studies showed that the composite was well segregated into normal metal and YBCO regions. The end result was an agglomeration of superconducting-normal-superconducting (SNS) junctions. For this paper, we focused on YBCO/Ag composites. The Ag regions were 3500 Å thick and extended above the YBCO layer that was 930 Å thick. The composite has been described as Ag mesas extending above a YBCO expanse. These films were first characterized and then pattern [3], [11]. Transition temperatures ranged from 87 K (no Ag) to 82 K (4000 Å Ag). The films were patterned into an H-shaped bridge configuration suitable for I-V measurements. The dimensions of the bridge were typically 1.0 mm wide and 1.5 mm long.

The patterned films were mounted in a cryostat and immersed completely in the liquid cryogen in order to eliminate temperature gradients due to local heating. Current-voltage (I-V) curves were taken under computer control. The current values were small, on the order of milliamperes; consequently the current direction could be easily reversed and the voltages averaged to eliminate the effect of any thermal voltages. Temperature was measured by means of a diode thermometer mounted very close to the sample under study, and changed by pumping on the liquid cryogen bath. The vapor pressure of the liquid and hence the temperature was held constant during the current sweep. Magnetic fields up to a maximum of 15 mT were applied at constant temperature to see how seriously these materials were degraded by small magnetic fields.

III. EQUATIONS AND MODELING

The functional dependence of the voltage on the current for the MAH model is a complex multiple integral expression that does not lend itself well to numerical evaluation. Likharev presents an expression in terms of a Fourier series that can be used for curve fitting [12]. A FORTRAN computer program suitable for curve fitting was written, and executed on a Macintosh 8100 computer. All the other computer fitting was accomplished using Kaleidagraph on a Macintosh II computer used for data acquisition and analysis.

A simplified expression of current ($I$) as a function of voltage ($V$) for the MAH model may be obtained for use in the ranges of interest of our experimental data:

\[ I = m_1 + m_2 \ln \left( \frac{V}{V_0} \right) + m_3 V \]  

(1)

where

\[ m_1 = \frac{2f_c}{R} - m_2 \ln \left( \frac{I_c R}{V_0} \right) \]  

(2)

\[ m_2 = \frac{2f_c}{\gamma R} \]  

(3)

and

\[ m_3 = \frac{1}{R} \]  

(4)

In this model, the parameters $R$, $I_c$, and $\gamma$ may be extracted from these fitting parameters. $R$ is the normal state...
resistance; \( I_c \), the critical current in the absence of thermal fluctuations; and \( \gamma \), the noise rounding parameter which is defined in equation (5).

\[
\gamma = \frac{E_J}{k_B T} = \frac{\phi_0 I_c}{2\pi k_B T}
\]  

(5)

where \( E_J \) is the Josephson coupling energy; \( \phi_0 \), the flux quantum; \( T \), the temperature; and \( k_B \), Boltzmann's constant. We note that \( I_c \) is not the critical current as defined in the usual sense, such as the current at some voltage, electric field or power criteria, but rather something that is derived from the model fit over the entire current-voltage curve.

The VG model is described by the equation:

\[
I = \left( \frac{m_4}{m_5 - \ln(V)} \right)^{m_6}
\]  

(6)

where

\[
m_4 = \gamma (I_c)^\mu,
\]  

(7)

\[
m_5 = \ln \left( V_0 \exp \left( \frac{\gamma}{I_c} \right) \right),
\]  

(8)

and

\[
m_6 = \frac{1}{\mu}.
\]  

(9)

In this model, \( \mu \) is a constant having a value predicted to be between 1 and 3.

The TAF model is described by the following equation:

\[
I = m_7 + m_8 \ln(V)
\]  

(10)

where

\[
m_7 = \frac{1}{\gamma} \ln \left( V_0 \exp \left( \frac{\gamma}{I_c} \right) \right),
\]  

(11)

and

\[
m_8 = -\frac{1}{\gamma}.
\]  

(12)

IV. RESULTS AND DISCUSSION

The application of small magnetic fields up to a maximum of 15 mT had a small but predictable effect on the I-V curves. At constant temperature, increasing magnetic field caused the I-V curve to shift to slightly lower current values. The study of magnetic fields on these composite materials is under way and will not be discussed further in this paper, which will be focused upon the temperature dependence of the I-V curves at zero magnetic field, as shown in Fig. 1.

The existence of interfaces between the Ag and YBCO suggested the presence of weak links due to the S-N-S nature of these composite films. This situation seemed to naturally lend itself to description by the MAH model. Both the full and the simple MAH were fitted to the data. The results differed in magnitude since approximations were made in the simple fitting equations that were not made in the full equation. The results also indicate trends shown in the next three figures which are consistent with what one might expect from physical intuition. For example, \( I_c \) increases with decreasing temperature, \( R \) decreases with decreasing temperature, and \( \gamma \) decreases with increasing temperature consistent with equation (5). These trends are illustrated in Figs. 2-4.

Similar fitting was carried out using the VG model. Unlike the simplified expression for the MAH model, the individual parameters in this model are not determined from the fitting.
parameters except for the parameter $\mu$. This parameter was found to have a temperature dependence shown in Fig. 5, which was inconsistent with the model as originally proposed.

The TAFF model did not fit the data very well. This is not surprising in retrospect if we examine (10) for the TAFF model and (1) for the simplified MAH model. These equations are identical except for the linear term containing $V$. Consequently, the TAFF model is unable to generate a better fit than the modified MAH model. Therefore we did not pursue this model any further.

In comparing the results of curve fitting for individual data sets, we found that the VG model provided a slightly better fit to the data than the MAH model. However the inability to extract quantities such as $I_c$ and $\gamma$ raises the issue of model usefulness. The MAH model has been shown to fit wide range of systems. These include multifilamentary superconductors [8], bulk superconductors [13], and thin film superconductors [14], as well as this inhomogeneous system. Furthermore, the model continues to offer the possibility of an intrinsic definition of critical current based, not on some arbitrary criterion such as an E-field or power criterion, but rather on the entire I-V curve.

V. CONCLUSIONS

The MAH model has been found to exhibit physically consistent trends for this YBCO/Ag inhomogeneous system. These trends are similar to those found in other systems. The fitting parameters can be expressed in terms of meaningful quantities that could be related to the physical characteristics of the system under study.

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REFERENCES


