Microwave surface impedance of high-quality YBa$_2$Cu$_3$O$_{7-x}$ thin films

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Abstract

The parallel plate resonator method has been used for measuring high quality YBa$_2$Cu$_3$O$_{7-x}$ (YBCO) thin films. The surface resistance and the real part of the conductivity show a non-monotonic behaviour with a broad peak around 45 K. The penetration depth and the real part of the conductivity vary linearly at low temperatures. The lowest penetration depth linear fitting has a slope value of 2.2 to 2.5 Å/K up to 20 K which is lower than previous measurements on YBCO single crystals. An interpretation of this smaller slope in terms of the generally accepted d-wave order parameter symmetry presents difficulties. © 1999 Published by Elsevier Science B.V. All rights reserved.

Keywords: YBa$_2$Cu$_3$O$_{7-x}$; Microwave surface impedance; Parallel plate resonator method

1. Introduction

Determining the symmetry of the superconducting order parameter is one of the main issues in understanding the mechanism that causes superconductivity in the high-$T_c$ cuprates.

One of the long-standing problems is the residual surface resistance [1] which has presumably an extrinsic origin such as twins, grain boundaries and other defects. The extrinsic losses can smear out the non-monotonic behaviour of $R_s(T)$ in YBCO single crystals [2], and they can influence in the same manner YBCO thin film properties. It was shown that this non-monotonic behaviour manifests itself as a broad peak in $R_s(T)$ around 40 K which is more conspicuous in $\sigma_s(T)$ [3].

2. Experimental

In our experiment, we measured high-quality YBCO thin films on LaAlO$_3$ substrates [4,5]. The best pair of such films used in our parallel plate resonator (PPR) gave a small residual loss of about 50 µΩ at 10 GHz. These residual losses are intermediate between two values reported for YBCO single crystals (200 µΩ [6], 10 µΩ [7] at 10 GHz). In our measurements with the PPR, we used two $1 \times 1$ cm$^2$ YBCO thin films with a Teflon spacer 25 µm thick in between them.

3. Results and discussion

The surface resistance of these films is shown in Fig. 1. The lower curve was obtained for a couple of
high quality YBCO thin films with the lowest residual losses. The non-monotonic behaviour, expected for high quality YBCO, is not so prominent in the $R_s(T)$ measurement, but appears clearly in $\sigma(T)$ as shown later. The upper curve was obtained for lower quality YBCO thin films. It shows a more monotonic $R_s(T)$ dependence. The residual losses are quite low for the lower curve, $R_{\text{res}} \leq 50 \ \mu\Omega$. For the upper curve, $R_{\text{res}} \leq 150 \ \mu\Omega$. The origin of $R_{\text{res}}$ in YBCO is not well understood. In one case a small reduction of $R_{\text{res}}$ in a YBCO single crystal is reported when introducing Ni or Zn impurities [3]. In another case it was shown that irradiation of two YBCO thin films by 25 meV $^{16}$O ions [8], suppresses the $R_s$ non-monotonic behaviour. One of the films showed a decrease in $R_{\text{res}}$ after the first irradiation, while in the second one, $R_{\text{res}}$ increased. Further irradiation leads $R_{\text{res}}$ to increase in both films. In another work, it was shown that the $R_{\text{res}}$ can increase due to lack of oxygen [9].

The change of the penetration depth with temperature tends to increase with increasing $R_{\text{res}}$. Fig. 2a and b show the temperature dependence of the penetration depth at the low temperature range. The two sets of data are related to the two $R_s(T)$ curves presented in Fig. 1. The slopes obtained from a fit to a linear temperature dependence are respectively equal to 2.2 Å/K for the lower $R_{\text{res}}$, and 3.8 Å/K for the higher $R_{\text{res}}$, in the temperature range from 5 to 20 K. Actually, a better linear fit is obtained for the lower $R_{\text{res}}$ sample in the range from 10 to 25 K, the slope is then 2.5 Å/K. For the higher $R_{\text{res}}$ sample, the data shows a positive curvature in the entire temperature range.

A linear penetration depth temperature dependence is predicted for a d-wave superconductor with lines of nodes [10], $\Delta (T)/\Delta(0) \propto \ln(2) T\Delta_0$ where $\Delta_0$ is the gap value. This is in agreement with the slope reported for a single crystal, taking $\Delta_0 = 22$ meV [11]. Impurities can alter this linear dependence to a quadratic temperature dependence one [3]. Unidentified imperfections can apparently cause the same quadratic behavior in YBCO thin films [10,12]. For an overdoped, high-$R_{\text{res}}$ YBCO thin film measured in our set-up a slope of $\sim 4.3$ Å/K was obtained [13]. The small slope reported here for the better sample is difficult to understand, if the linear...
behavior is interpreted as being due to a d-wave symmetry. In the unitary limit [14], as disorder is increased, the change of \( \lambda \) with temperature should become smaller, while it appears experimentally to become larger. A different interpretation of the linear behavior was proposed some time ago by several authors [15–17], as arising from phase fluctuations of the order parameter, but the calculated slope was smaller that the one measured on single crystals, by at least one order of magnitude; this interpretation was therefore discarded. Yet, the predicted slope varies as \( \lambda(0)^3 \), and is therefore quite sensitive to a weak disorder, surely present in the films, known to increase the value of \( \lambda(0) \). An increase by 30\% would be sufficient to obtain a slope of the order of 1 to 2 \( \text{Å/K} \). Other possible explanations for the smaller slope, in the framework of a d-wave interpretation, are a larger gap [18,19], or the presence of a twin-related large s-wave component.

The non-monotonic behaviour of \( \sigma_\text{T}(T) \) is shown in Fig. 3 for the best set of samples (calculated for \( \lambda(0) = 1500 \text{ Å} \)). \( \sigma_\text{T}(T) \) has its maximum value at \( \sim 45 \text{ K} \) in agreement with the results for a pure YBCO single crystal at 34.8 GHz [3]. Yet, the smaller peak amplitude indicates a smaller value of \( \tau_{\text{res}} \), as compared to the pure single crystal case [2].

We note (Fig. 3) the linear slope of the real part of the conductivity at low temperatures (below 20 K). This linear slope was measured also on an YBCO single crystal [3]. According to the theoretical prediction for a d-wave gap, \( \sigma_\text{T}(T) \) should vary as \( T^2 \) at the microwave frequency range [14]. We show also in Fig. 3 \( \sigma_\text{T}(T) \) for the higher \( R_{\text{res}} \) sample calculated for \( \lambda(0) = 2000 \text{ Å} \). The scattering rate of the lower \( R_{\text{res}} \) thin films is shown in Fig. 4. One can see the predicted abrupt change below \( T_c \) and its saturation below 45 K.

4. Conclusion

We have presented surface impedance measurements on high quality YBCO thin films. These films have residual losses comparable to those of single crystals. The linear \( \Delta\lambda(T) \) behaviour that we observe is in qualitative agreement with the d-wave superconducting model, but the slope that we observed in our best samples (2.2 to 2.5 \( \text{Å/K} \)) is smaller than reported for single crystals. A non-monotonic behaviour in \( \sigma_\text{T}(T) \) was observed for the best set of samples. It can be a good indication for the quality of the thin films. The linear \( \sigma_\text{T}(T) \) in the low temperature range is inconsistent with the quadratic temperature dependence predicted by the d-wave theory.

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References