MICROWAVE PROPERTIES OF YBCO CRYSTALS GROWN IN BaZrO₃ CRUCIBLES: INFLUENCE OF c-AXIS CURRENTS

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Abstract—Measurements of the $ab$-plane complex microwave conductivity of high quality YBa$_2$Cu$_3$O$_{6.95}$ single crystals indicate the presence of a pairing temperature scale around 65 K in addition to the bulk $T_c$ of 93.4 K. Qualitatively similar behavior is seen for the case when microwave current flow in both $ab$-plane and along the c-axis. Influence of c-axis currents tends to broaden the feature in the superfluid density around 65 K. The extracted c-axis low temperature penetration depth, $\lambda_\text{c}(T)$, shows a linear dependence with a slope nearly 10 times larger than that of $\lambda_\text{ab}(T)$. © 1998 Elsevier Science Ltd. All rights reserved

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1. INTRODUCTION

The microwave response in cuprate superconductors in general and YBCO in particular, has recently become a topic of renewed interest with the emergence of new results obtained in high quality YBa$_2$Cu$_3$O$_{6.95}$ single crystals grown in BaZrO$_3$ crucibles [1, 2]. The new growth method avoids the usual problem of crucible corrosion and leads to crystals with very clean surfaces and high purities [3].

There has been considerable progress in characterizing the properties of these new generation YBCO single crystals using a variety of experimental probes. In a recent publication [2], we have provided a comprehensive summary of the microwave properties of YBCO crystals grown in BaZrO$_3$ (YBCO/BZO) and in the commonly used YSZ crucibles (YBCO/YSZ).

Two key results that emerge are the observation of the following new features in the $ab$-plane microwave properties of YBCO/BZO single crystals at 10 GHz:

1. A new pairing temperature scale at around 65 K in addition to the bulk superconducting $T_c$ of 93 K.
2. A new quasiparticle conductivity peak in the superconducting state at around 80 K in addition to the low temperature peak around 35 K and a sharp peak just below $T_c$. These three conductivity peaks are present in all high quality YBCO crystals.

Based on these new observations, we have suggested that it is incorrect to ascribe the full temperature dependence of the microwave surface impedance, $Z_s = R_s + iX_s$, and consequently the complex conductivity, $\sigma(T) = \sigma_x(T) - i\sigma_y(T)$, to a single order parameter of any kind [1, 2]. Instead, our results strongly point to the presence of at least two pairing energy scales in YBCO. It may be argued that if this is the case, then there should be manifestations of multiple pairing energy scales in other surface and bulk experimental probes too. This is indeed the case and the literature is replete with results which are consistent with the notion of multiple energy scales or mixed order parameter symmetries [4–6]. Some examples include:

1. Tunneling experiments which typically show multiple gap features [4].
2. Demonstration of c-axis Josephson coupling between a conventional superconductor, Pb, and YBCO [5].
3. Thermal conductivity measurements on optically doped YBCO crystals ($T_c > 90$ K) have yielded important information about the significance of the temperature around 60 K below which extra pairing occurs [7, 8].
4. Raman measurements have been found to be consistent with an $s + d$ order parameter symmetry in YBCO [9, 10] and in HgBCCO [11].

We have considered various scenarios based on a mixed order parameter symmetry and obtained quantitative fits with the microwave data on YBCO/BZO crystals [2]. It is important to note that the microwave results on YBCO/YSZ crystals can also be described within the framework of the two-component model presented in Ref. [2]. In addition to the new features seen in the temperature dependence of the microwave surface impedance, non-linear microwave responses in the crystals exhibit a remarkably coherent,
Josephson-like response for both $ab$-plane and $c$-axis currents [12].

The crystals used in our measurements are twinned and while this rules out the possibility of extracting the individual $a$- and $b$-axis contributions to the $ab$-plane penetration depth, the $c$-axis contribution and the anisotropy relative to the $ab$-plane can be estimated by applying the microwave field parallel to the $ab$-plane (as shown in the schematic of Fig. 1).

In this paper, we extend our studies to the case where the YBCO/BZO crystal is mounted, such that microwave currents flow in the $ab$-plane and along the $c$-direction. The purpose is to study the influence of $c$-axis properties and to determine the low temperature variation of the penetration depth.

2. EXPERIMENTAL

The single crystals of optimally doped $\text{YBa}_2\text{Cu}_3\text{O}_{6.95}$ were grown using a melt growth technique in homemade $\text{BaZrO}_3$ crucibles and details of crystal growth and oxygen annealing have been published elsewhere [3]. Typical dimensions of the twinned YBCO/BZO crystals used in this measurement were $1 \text{ mm} \times 1 \text{ mm} \times 0.1 \text{ mm}$. The bulk superconducting $T_c$ was around 93 K with a very sharp transition seen in magnetic susceptibility and our own microwave measurements.

The microwave experiments are done in a superconducting Nb cavity resonator, operating at 10 GHz, using a cavity perturbation technique [13]. This method is well suited to measure the surface impedance of single crystals and has been extensively validated in precision measurements of surface resistance, $R_s$, and reactance, $X_s$, in cuprate [1, 14] and borocarbide superconductors [15]. $R_s(T)$ is measured from the temperature-dependent quality factor, $Q$, using the relation $R_s(T) = \Gamma Q^{-1}(T) - Q_b^{-1}(T)$ (where $Q_b$ is the background quality factor of the resonator without the sample and could be as high as $10^5$). The change in penetration depth, $\Delta \lambda(T)$, can be obtained from the shift in resonant frequency and is typically given by the relation, $\Delta \lambda(T) = \xi f(T) f_0(T)$. The geometric factors $\Gamma$ and $\xi$ are determined by the cavity mode, sample size and location within the cavity. In the present case, measurements were done in the $\text{TE}_001$ mode with the sample at the midpoint of the cavity axis where the microwave magnetic fields have a maximum and electric fields are zero. For the results presented in this paper, the crystals are oriented such that $H_{ab}$ is parallel to $c$ and currents flow both in the $ab$-plane and $c$-axis. A schematic of the experimental set-up is shown in Fig. 1.

3. RESULTS AND DISCUSSION

The real and imaginary parts of the complex surface impedance for a YBCO/BZO single crystal, measured in the same experiment, are presented in Fig. 2. The top panel shows $R_s$ and $X_s$ data plotted in a semi-log scale, and the bottom panel shows the same data in a linear scale. Note the microwave currents are present in the $ab$-plane and $c$-axis.
Fig. 3. Superfluid density, assuming an estimated $\lambda(0)$ value of 1200 for the $(ab + c)$ case. The feature associated with enhanced pairing is shifted below 50 K.

The panel shows the $R_s$ and $X_c$ data plotted against temperature in a semi-log scale to highlight the features at low temperatures. The bottom panel shows the low temperature portion of the same data plotted in a linear scale. All the new features that we have identified before as characteristic features seen in YBCO/BZO single crystals [1, 2] are present for this crystal orientation too. These include the peak in $R_s$ at around 35 K, a rapid rise in $R_s(T)$ between 50 and 80 K, and a broad bump in $X_c$. It should be noted that we have chosen to present the data for the specific crystal (AE180) which was annealed at 100 bar of oxygen for a period of 40 h at 700°C. This is particularly significant as the possibility of forming oxygen vacancy clusters is eliminated in this process and as a consequence, the “fishtail” anomaly in magnetization is suppressed [16]. But the data are representative of other YBCO/BZO crystals too and in our contention, the presence or absence of the “fishtail” feature itself (which is a property of the vortex pinning due to microstructural inhomogeneities associated with oxygen vacancy clusters [16, 17]), has no direct bearing on the microwave results where the applied microwave field, $H_M$, is below the lower critical field, $H_{c1}$.

The generic features seen in the $R_s$ and $X_c$ data of Fig. 2 translate to the occurrence of enhanced pairing at a temperature lower than the bulk $T_c$, and the presence of three microwave conductivity peaks in the quasiparticle response in the superconducting state. A detailed analysis of our results in terms of complex conductivities for the case of $ab$-plane currents only, has been presented by us in earlier publications [1, 2]. We do not attempt to present such an analysis here, but the overall qualitative similarity in the observed features for the $(ab + c)$ geometry also indicates that the presence of $c$-axis currents do not significantly affect the new features that we consistently see in the microwave response of YBCO/BZO single crystals. However, there are some qualitative and quantitative differences and these are represented in the plot of superfluid density [$\lambda(0)/\lambda(T)$], shown in Fig. 3.

3.1. Low temperature penetration depth and superfluid density

A comparison of this data with the plot of $\sigma_1 \propto (\lambda^2(0)/\lambda^2(T))$ for the $ab$-plane results for the same crystal (AE180) presented in Ref. [2] show that, while the curves display overall similarities, there are marked differences as well. In particular, the kink feature around 65 K which we identified as the onset of an additional superconducting component (in the $ab$-plane case), is rather broad in the data shown in Fig. 3. This may indicate that the influence of $c$-axis currents or the incoherent nature of $c$-axis transport itself tend to smear the onset of the second pairing channel below the bulk $T_c$. However, it should be noted that the estimated London penetration depth, $\lambda(0)$, for the $(ab + c)$ geometry is around 1000–1200, which is comparable to that obtained for pure $ab$-plane currents only. This would indicate that the pair conductivity $\sigma_1$ rises to roughly the same value at low temperatures in both cases. In Fig. 3, $\lambda(0) = 1200$ was chosen to obtain the curve. It should be noted that the choice of $\lambda(0)$ does not affect the
temperature dependence of the change in penetration depth $\Delta T(T)$.

The low temperature variation of the penetration depth $\lambda_{ab+}(T)$ for the temperature region, $T < 0.3 T_c$, shows a strong linear dependence with a much larger slope than that of $\lambda_{ab}(T)$ in the same temperature range. This is also reflected in the $1/\lambda^2$ plot of Fig. 3 where a steep $(1 - T)$ behavior is clearly seen for $T < 30$ K. To illustrate this further and make a direct comparison, we have shown the change in penetration depth $\Delta \lambda(T)$ up to 20 K for both geometries in Fig. 4. Both $\lambda_{ab+}(T)$ and $\lambda_{ab}(T)$ show a linear variation, with the former having a slope nearly three times larger than the latter. (Note that the corrections due to demagnetization effects are always taken care of in our presentation of the penetration depth results. Finite thickness corrections are not required, as at 10 GHz, the $ab$-plane and $c$-axis skin depths are far less than the sample dimensions.) This observation is in excellent agreement with earlier results reported by Mao et al. [18] on YBCO crystals grown in YSZ crucibles. It should be pointed out that their measurement technique was identical to ours, with even the operating frequency (9 GHz) close to ours (10 GHz).

We use the notation $\lambda_{ab+}(T)$ to depict the geometry with both $ab$-plane and $c$-axis currents and this is identical to the term $\lambda_{ab}(T)$ used in the paper of Mao et al. [18].

Ideally, with the penetration depth measurements in the two geometries viz. $\lambda_{ab+}(T)$ and $\lambda_{ab}(T)$, it should be possible to extract the pure $c$-axis penetration depth $\lambda_c(T)$ from the simple expression:

$$\lambda_c = \frac{[\lambda_{ab+}(T + w) - \lambda_{ab}]}{d}$$

where $l$, $w$ and $d$ are the length, width and thickness of the crystal respectively. The $c$-axis penetration depth $\lambda_c(T)$ extracted in this manner is also shown in Fig. 4. The data clearly show a linear variation, albeit with a large slope, up to 25 K. Due to the presence of the bump at intermediate temperatures, it is not possible to extract the full temperature dependence up to $T_c$ with this simple analysis.

3.2. Discussion of the $c$-axis contribution

The anisotropic nature of cuprate superconductors has led to extensive investigation of the in-plane and out-of-plane transport properties in these materials [19]. Experimental have confirmed that in the highly anisotropic BSCCO system, the $c$-axis transport can be very well explained by considering the material as a stack of Josephson-coupled 2-D superconducting layers [20]. Jacobs et al. [14] have measured the complete $T$ dependencies of $\lambda_{ab}(T)$ and $\lambda_c(T)$ and have demonstrated that the $c$-axis penetration depth is linear at low temperatures. This is in good agreement with the calculation of the superfluid density along the $c$-axis based on an interlayer tunneling model [21].

YBCO is far less anisotropic and the influence of $c$-axis transport on the microwave response is an interesting issue. Our data on YBCO/BZO presented in Fig. 4 indicates that $\lambda_c(T)$ at low temperatures is linear (as in the case of BSCCO). We would like to again point out that our observation is in good agreement, even quantitatively, with that of Mao et al. [18] on YBCO/YSZ crystals. Very recently, Hosseini et al. [22] have reported $c$-axis penetration depth measurements on $dc$-twinned YBCO/YSZ crystals, which display a $T^2$ dependence of the $c$-axis penetration depth at low temperatures, in contrast to the present work and that of Ref. [18]. They have claimed this as evidence for incoherent behavior of the $c$-axis superfluid density.

The superfluid anisotropy in YBCO has also been specifically treated within the framework of proximity effect and pair tunneling models [23]. In the proximity model, the intrinsically superconducting plane and chain layers are coupled through single electron tunneling [24] in the $c$-direction. The $T$-dependence of our data is qualitatively consistent with the calculated $c$-axis penetration depth that comes out of this model [23].

4. CONCLUSIONS

In conclusion, our measurements of the microwave properties of ultrapure YBCO single crystals grown in BaZrO$_3$ crucibles consistently display some remarkable features not directly revealed in crystals grown in YSZ crucibles. The key observations are a new pairing temperature around 65 K in addition to the bulk $T_c$ of 93 K and the presence of a third microwave conductivity peak associated with the quasiparticles. Anisotropy effects resulting from the presence of $c$-axis microwave currents do not change the qualitative nature of these new features. The low temperature $\lambda_c(T)$ also exhibits a linear variation with a slope far greater than that of $\lambda_{ab}(T)$.

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REFERENCES


