Physica C 235-240 (1994) 2013-2014
North-Holland

PHYSICA C

Temperature Dependence of the Surface Impedance of $Nd_{1.85}Ce_{0.15}CuO_{4-y}$ and $YBa_2Cu_3O_{7-\delta}$

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We have measured the surface impedance of $YBa_2Cu_3O_{7-\delta}$ (YBCO) single crystals, $Nd_{1.85}Ce_{0.15}CuO_{4-y}$ (NCCO) thin films and single crystals, and Nb single crystals at 9.6 GHz using a superconducting cavity perturbation technique. Our results on Nb are in good agreement with s-wave BCS theory. The magnetic penetration depth in the ab-plane in YBCO single crystals exhibits a linear temperature dependence at low temperatures, and is consistent with clean 2D d-wave superconductivity. Both thin films and single crystals of the electron-doped cuprate NCCO show detailed agreement with the predictions of single-gap isotropic s-wave BCS electrodynamics over the measured temperature range up to T_c.[1-3]

1. INTRODUCTION

The pairing symmetry of the ground state wavefunction is one of the central points of interest in the study of cuprate superconductors. As a consequence of the single-sign energy gap in an s-wave BCS superconductor, a wide variety of thermodynamic properties show exponentially activated behavior. Recently a number of experimental and theoretical results suggest a d-wave pairing state symmetry in the hole-doped cuprate superconductor YBCO. According to the d-wave model, for an unconventional singlet superconductor with the point group symmetry of YBCO, the only nodes allowed are line nodes, distributed on the Fermi surface in such a way that the penetration depth should exhibit a linear temperature dependence at low temperatures.[4] In this paper, we shall report our microwave surface impedance measurements of electron-doped cuprate NCCO, hole-doped cuprate YBCO, and conventional low temperature superconductor Nb.

2. EXPERIMENTAL

The single crystal Nb sample is about 3 mm x 3 mm x 0.2 mm. A typical size of NCCO film deposited on YSZ-buffered sapphire substrates is about 3 mm x 5 mm x 2700 Å.[3] NCCO crystals grown by the directional solidification technique have a typical size of 2 mm x 2 mm x 15 μm.[1,2] YBCO single crystals are made by the standard flux method in a zirconia crucible with T_c in the range of 92-94 K by AC, DC transport, and DC SQUID measurements.[2] The size of the YBCO sample is about 1 mm x 1 mm x 17 μm.

All the measurements were done in a bulk superconducting Nb cavity at 9.6 GHz. The surface resistance and the penetration depth data are obtained via the simultaneous measurement of the quality factor Q and the resonant frequency f_0, as $R_s = \Gamma(1/Q-1/Q_{cav})$, $\Delta X_s = 2\pi f\mu_0\Delta\lambda$ and $\Delta\lambda = -\zeta(f_0-f_0(4.2K))=-\zeta\,\Delta f_0$. Here Q_{cav} is the quality factor of cavity without a sample with a typical value 2.3×10^7 at 4.2 K, 9.6 GHz, and f_0 is the resonant frequency. Γ and ζ are the geometric factors which depend on the resonant mode, the size of the cavity, and the sample size and shape. With the high Q and stable signals in the frequency domain, we have a resolution $\Delta R_s \approx 10\,\mu\Omega \sim 50\,\mu\Omega$ and $\Delta\lambda \approx 1\sim4$Å, depending on the size of the sample.

3. RESULTS AND DISCUSSION

Figs. 1 and 2 show the low temperature behavior of various samples: single crystals of Nb, NCCO and YBCO, as well as NCCO thin films. The data are plotted in a manner to normalize away different geometry coefficients and T_c's. While there are obvious similarities between data from Nb and NCCO samples, we see a dramatic difference between YBCO and the rest of samples.

In Fig 1, as $\Delta\lambda = -\zeta\,\Delta f$, the penetration depth in the ab plane λ_{ab} of YBCO crystals shows a linear temperature dependence for T≤45K. The slope

0921-4534/94/\$07.00
SSDI 0921-4534(94)01573-2

$\Delta\lambda/\Delta T$ is about 5Å/K, in good agreement with the clean d-wave model.[4,5] For the frequency shift data on NCCO and Nb, the best fit can be obtained with the BCS s-wave type exponential dependence, $\delta f(T) \propto T^{-1/2} \exp[-\Delta(0)/k_BT]$ for $T/T_c \leq 0.5$ with an activation barrier $2\Delta(0)/k_BT_c \approx 4.0 \sim 4.2$ for both Nb and NCCO. Functional forms such as T^n can

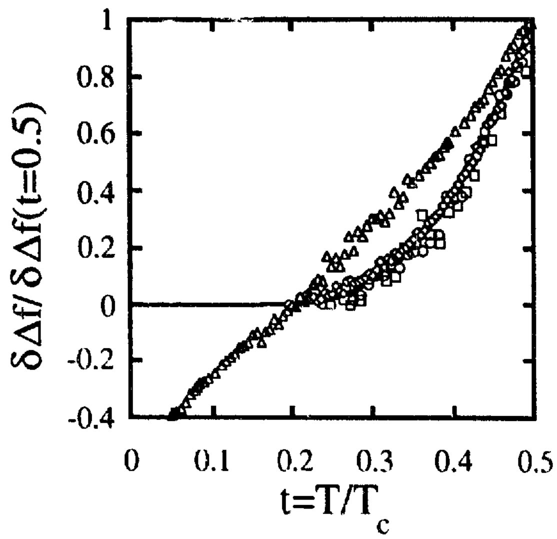

Fig.1. $[\Delta f(t)-\Delta f(t=0.2)]/[\Delta f(t=0.5)-\Delta f(t=0.2)]$ for $T/T_c \leq 0.5$ for NCCO film (squares), NCCO single crystals (diamonds), Nb single crystal (circles) and YBCO single crystals (triangles). Solid line is the exponential fit mentioned in the text.

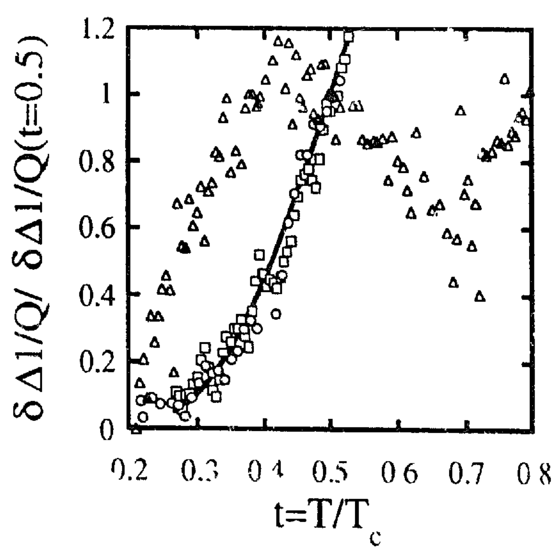

Fig.2 $[\Delta 1/Q(t)-\Delta 1/Q(t=0.2)]/[\Delta 1/Q(t=0.5)-\Delta 1/Q(t=0.2)]$ for $T/T_c \leq 0.5$ for NCCO film (squares), Nb single crystal (circles) and YBCO single crystals (triangles). Solid line is the exponential fit

also yield equally good fits to the data if $n \geq 4$, which is indistinguishable from the exponential.

In Fig. 2, the best fits to $R_s(T)$ for Nb and NCCO samples are consistent with the exponential behavior $R_s(T) \propto T^{-1} \exp(-\Delta(0)/k_BT)$ with the gap ratio $2\Delta(0)/k_BT_c = 4.0 \sim 4.2$, as well as the power-law dependence with $n \geq 4$. For YBCO, however, the temperature dependence of the surface resistance looks quite different. It is sub-linear from 4.2K up to 30 K. The peak around 40 K and the dip around 70 K, which resemble the features of Univ. of British Columbia's results,[6] are distinctly different from that of a conventional superconductor.

Remarkable agreement between the single-gap BCS calculations and the experimental results over the measured temperature range for these new NCCO films was demonstrated in reference 2. The value of the electrodynamic parameters for these films are very similar to those of our earlier films, leading us to conclude that our results are independent of disorder.[1,2]

4. SUMMARY

The behavior of the λ and R_s of NCCO is extremely similar to that of BCS s-wave superconductor, but that of YBCO shows marked differences. The results on NCCO appear in both thin films and single crystals, and the result on clean YBCO crystals have now been seen by two groups,[2,6] leading us to believe we may have intrinsic results. If this is the case, then a broad theory which incorporates both s-wave and d-wave cuprates may need to be developed.

ACKNOWLEDGEMENT

We would like to acknowledge the NSF NYI program (DMR-9258183) for support.

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