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Surface impedance of $R_1(Nd_xBa_{2-x})Cu_3O_{7-\delta}$ (R = Nd, Y) thin films

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Abstract

We have studied the effect of Nd/Ba substitution on the superconducting properties of $R_1(Nd_xBa_{2-x})Cu_3O_7$ (R = Nd, Y) thin films by using microwave penetration depth and surface resistance measurements. Data on samples characterised by a Nd-excess of 4–5% have been collected by using a microstrip resonator at frequencies of 1.44 and 9.7 GHz and a symmetric dielectric resonator technique in TE_{011} mode at 19.8 GHz. A quadratic bT^2 low temperature dependence of the penetration depth is observed for the Nd-rich samples, with the coefficient b decreasing with the frequency. The data can be reasonably explained in a d-wave framework supposing that Nd at Ba site behaves, both in $Nd_{1+x}Ba_{2-x}Cu_3O_7$ and $Y_1(Nd_xBa_{2-x})Cu_3O_7$, as a resonant impurity, as confirmed by scanning tunnelling spectroscopy. The changes of the temperature dependence of the penetration depth with the frequency can be explained with a two fluid approach taking into account the frequency dependence of the complex conductivity.

Keywords: RBCO; Microwave surface impedance; Nd/Ba substitution

The temperature dependence of the surface impedance of the high T_c superconductors (HTS) gives unique information on the properties of the pair condensate and on the quasi-particle scattering in these materials. The transport properties of the HTS are affected by various kind of defects, like structural imperfection and even localised atomic substitutions [1–4]. In many deposition techniques the growth proceeds in conditions far from the thermodynamic equilibrium, therefore cationic disorder can be a common point like defect even in epitaxial films with a nominal stoichiometric composition. In the $R_{1+x}Ba_{2-x}Cu_3O_{7-\delta}$ (RBCO, R = rare earth and Y) compound Nd/Ba substitution may promote a 2D "layer by layer" growth with suppression of screw dislocations and smooth surfaces on large areas, which can be very important for applications [5]. The study of the microwave response of $R_1(Nd_xBa_{2-x})Cu_3O_{7-\delta}$ (Re = Nd, Y) samples having a given amount of Nd excess at Ba site has therefore two important outcomes, i.e. the interest in the use of materials alternative to YBCO for applications and the interest in the understanding of the role of cationic disorder on the superconductivity of the RBCO films.

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We present results on the temperature dependence of the penetration depth and of the surface resistance in $Nd_{1.04}Ba_{1.96}Cu_3O_{7-\delta}$ (NBCO) and $Y_1(Nd_{0.05}Ba_{1.95})Cu_3O_{7-\delta}$ (YNBCO) epitaxial films. To collect reliable data at different frequencies we have employed two different techniques, i.e. a microstrip open resonator with fundamental quasi-TEM mode at about 1.44 GHz, described in detail in [6], and a symmetric cylindrical copper dielectric loaded closed cavity operating in the TE_{011} mode at 19.8 GHz [7]. In both techniques the screening superconducting currents are along the *ab* plane, so the properties of the superconducting CuO_2 layers and eventually of the CuO chain layers are probed.

The NBCO and YNBCO samples have been deposited on (1 0 0) $LaAlO_3$ substrates by dc magnetron sputtering and diode high pressure oxygen sputtering. The details of the deposition procedures are reported in [5] and [7] respectively. The NBCO films exhibit inductively measured T_c higher than 86 K. The YNBCO samples deposited by high pressure oxygen sputtering have very reproducible T_c of 86–87 K in a wide range of deposition conditions.

In Fig. 1 the results on the temperature dependence of the surface resistance of a YNBCO film measured at 1.44 and 9.7 (open resonator) and 19.8 GHz (closed cavity) are shown. In the former case the measurements have been performed using a very low input power (−40 dB m at 1.44 GHz and −20 dB m at 9.7 GHz), in order to minimize additional contributions to losses related to the peaking of the current density at the microstrip edges. In the dielectrically loaded cavity the residual surface impedance of the two films used in the symmetric configuration has been determined exactly by using an identical Nb dielectric resonator operating at temperatures below 4.2 K. Consequently, data taken with the copper dielectric resonator have been corrected in order to match the low temperature surface resistance values. The temperature dependence of the surface resistance is quite complicate because of the dependence of the inelastic scattering rate in HTS. For this reason we do not present here an analysis of the surface resistance data. Further work on this aspect is still in progress. We wish to underline that the surface resistance of our films is comparable to the best YBCO films, for example at 77 K R_s (9.7 GHz) = 0.14 mΩ and R_s (19.8 GHz) = 1.4 mΩ.

In Fig. 2 we show the change of the penetration depth of a Nd rich NBCO film, a YNBCO film and a stoichiometric NBCO film deposited by pulsed laser deposition [8] and measured by the microstrip resonator technique at 1.44 GHz. The linear temperature dependence of the penetration depth of the stoichiometric sample is replaced by a quadratic temperature dependence in the case of the disordered YNBCO and NBCO films. It is interesting to note that the low temperature behaviour for the two different kind of Nd-rich samples

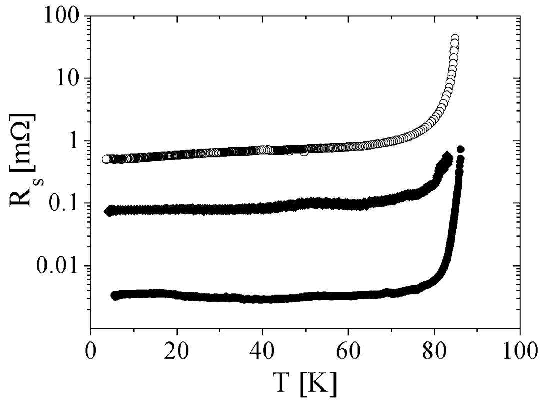

Fig. 1. Temperature dependence of the surface resistance of a YNBCO film measured at 19.8 GHz (○), 9.7 GHz (◆) and 1.44 GHz (●).

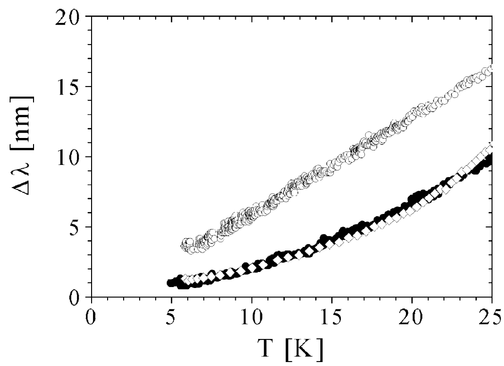

Fig. 2. Temperature dependence of the penetration depth changes at low temperature for a stoichiometric NBCO film (○), a $Y_1(Nd_{0.05}Ba_{1.95})Cu_3O_7$ (◇) and a $Nd_{1.04}Ba_{1.96}Cu_3O_7$ (●).

is identical. Since they have almost the same amount of Nd excess at Ba site, it is possible to conclude that the quadratic temperature dependence is due to the presence of Nd excess at Ba sites. As reported in [8] it is possible to explain quantitatively the data by supposing that the Nd excess act as quasi-particle scattering scalar impurity in the unitary limit in the framework of a d-wave model, as confirmed by scanning tunnelling spectroscopy [9].

It turns out however that at low temperature the penetration depth dependence is strongly affected by the frequency f as shown in Fig. 3 for the YNBCO sample. The temperature data, exhibiting a quadratic temperature dependence, tend to flatten at high frequency and can be approximately reproduced by a bT^2 law with the coefficient b decreasing with f. It is very interesting to note that there is a marked change in the low temperature behaviour from 9.7 to 19.8 GHz, whereas data at 1.44 and 9.7 GHz are only slightly different, with larger slope for the lower frequency curve. In a simple two fluid model, λ is expected to change with the frequency according to the equation:

$$\left[\frac{\lambda(T,\omega=0)}{\lambda(T,\omega)}\right]^2 = \frac{1}{1+(\omega\tau)^2} + \frac{(\omega\tau)^2}{1+(\omega\tau)^2}\left[\frac{\lambda(T,\omega=0)}{\lambda(T=0,\omega=0)}\right]^2 \tag{1}$$

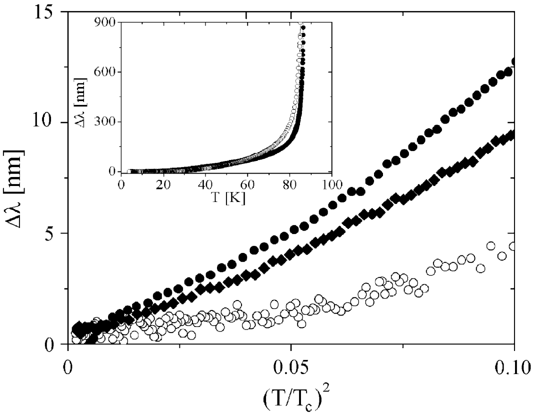

Fig. 3. Penetration depth changes for the YNBCO film vs $(T/T_c)^2$ measured at 19.8 GHz (○), 9.7 GHz (◆) and 1.44 GHz (●).

where $\omega = 2\pi f$, τ is the relaxation time and $\lambda(T,\omega)$ is frequency dependent penetration depth. In the limit $\omega\tau \ll 1$, $\lambda(T,\omega) = \lambda(T,\omega=0)$, however due to the quasi-particle excitation near the gap nodes, a crossover between the limits $\omega\tau \ll 1$ to $\omega\tau > 1$ may occur at low temperature for our YNBCO sample measured at the highest frequency of 19.8 GHz, while the limit $\omega\tau < 1$ is always realised at frequency <10 GHz. When $\omega\tau \ll 1$ the temperature dependence of the penetration depth is mainly due to the relaxation time which is known to be almost constant at low temperature. However in order to explain quantitatively the data it is necessary to extract directly the scattering rate at each frequency from the surface impedance data. This is not entirely straightforward since a measure of the surface impedance with accurate elimination of residual extrinsic losses is needed. Further work is still in progress in this direction.

In conclusion, we have shown the Nd/Ba cationic disorder induces scattering in the unitary limit in both NBCO and YBCO films at low frequency. Moreover, the penetration depth is affected by the change of frequency in a manner qualitatively explainable supposing that a crossover from the limit of $\omega\tau \ll 1$ to $\omega\tau > 1$ occurs at low temperature in the data taken at 19.8 GHz. On the contrary at frequencies lower than 10 GHz the condition $\omega\tau \ll 1$ seems to be verified in the full temperature range since the effect of frequency is much less pronounced.

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