Microwave surface impedance anisotropy of $YBa_2Cu_3O_x$ single crystals with different oxygen content

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Abstract

The linear microwave response of ultra high-quality $YBa_2Cu_3O_x$ single crystals grown in $BaZrO_3$ crucibles is measured at 9.4 GHz in rf magnetic fields parallel and perpendicular to the *ab*-plane in the temperature range $5\leq T \leq 200$ K. Having found the analytic solution for the magnetic field distribution on the sample surface we determine both the surface impedance $Z_{ab} = R_{ab} + iX_{ab}$ in the *ab*-plane and $Z_c = R_c + iX_c$ along *c*-axis of the crystals. For the first time the evolution of the $Z_{ab}(T)$ and $Z_c(T)$ dependences on the same sample and in a wide range of oxygen content is obtained. For $x = 6.95$ (optimum oxygen content) the temperature dependence of the imaginary part $\sigma''_c(T)/\sigma''_c(0)$ of the *c*-axis conductivity is found to be strikingly similar to that of $\sigma''_{ab}(T)/\sigma''_{ab}(0)$ and becomes more convex with x lowering.

Key words: surface impedance anisotropy; microwave conductivity; $YBa_2Cu_3O_x$; doping

In the scope of high-T_c superconductors, the problem to find out the mechanisms of quasiparticles transport along crystallographic axes of these anisotropic compounds remains unresolved. Microwave measurements were proved to be very informative when studying superconductors. They revealed linear low temperature dependence of the magnetic field penetration depth λ_{ab} across the cuprate planes in $YBa_2Cu_3O_{6.95}$ (YBCO). This fact is ascribed now to *d*-wave angular dependence of the order parameter $\Delta(\mathbf{k})$. In contrast to *ab*-plane response the *c*-axis properties measurements are rather controversial. Both linear and power law $\lambda_c(T)$ dependences were presented[1].

Having analyzed carefully the electrodynamical aspects of microwave measurements we found that one of the possible sources of this contradiction is a non-exact determination of the electromagnetic field on the surface and in the volume of the sample investigated. In microwave experiment the measured quantities are the quality factor and frequency shift of the resonator with the sample inside. We calculated the field distribution on the surface of the sample with dimensions $b \gg a > c$ placed in microwave magnetic field $\mathbf{H}_\omega||\mathbf{c}$. It enables us to calculate sample geometrical factor and, hence, obtain $Z_{ab}(T)$ dependence from the measurements at $\mathbf{H}_\omega||\mathbf{c}$. Knowing the value of $Z_{ab}(T)$ we can get the *c*-axis surface impedance components from the quantities measured for the same sample at $\mathbf{H}_\omega||\mathbf{b}$. For this we use a procedure proposed in Ref. [2]. It takes correctly account of the size effect which becomes apparent at $T > 0.9\,T_c$. In more detail all these calculations will be given elsewhere[3]. The technique discussed has two main advantages: (i) the possibility to measure surface impedance anisotropy in both normal and superconducting states, which enables to obtain not only the change of penetration depths but also their absolute values and (ii) the ability to obtain the evolution of the surface impedance tensor with doping level on the same sample. With the aim of this technique we present in this paper the results of high precision measurements of surface impedance tensor of $YBa_2Cu_3O_x$ at a frequency of 9.4 GHz as a function of temperature in a wide range of oxygen content x.

Ultra high quality YBCO single crystals were grown

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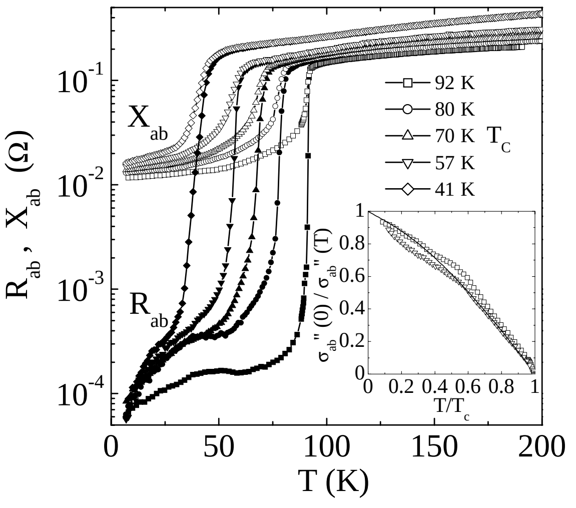

Fig. 1. Real $R_{ab}(T)$ (solid symbols) and imaginary $X_{ab}(T)$ (open symbols) parts of the ab-plane surface impedance of $YBa_2Cu_3O_x$ single crystal. Inset shows $\sigma''_{ab}(T)/\sigma''_{ab}(0)$ dependences for the cases of $T_c = 92$ and 58K. $\sigma''(T)/\sigma''(0)$ for the case of clean d-wave is shown by solid line.

using $BaZrO_3$ crucibles [3]. The dynamic susceptibility measurements showed $T_c \simeq 92$K and the width of the transition less than 0.1 K at 100 KHz. After successive anneals in the air at 520, 550, 600 and 720°C transition temperature reached 80, 70, 57 and 41 K respectively without significant transition broadening.

The surface impedance $Z_{ab} = R_{ab} + iX_{ab}$ temperature dependence of YBCO single crystal is shown in Fig. 1. In the normal state we have $R_{ab}(T) = X_{ab}(T)$ which implies the validity of the normal skin-effect condition. The value of residual losses $R_{ab}(T \to 0)$ does not exceed 40 $\mu\Omega$. In the case of optimum oxygen content $R_{ab}(T)$ dependence has a broad peak at $T \sim T_c/2$ which vanishes with x lowering. Both $R_{ab}(T)$ and $\lambda_{ab}(T) = X_{ab}(T)/\omega\mu_0$ dependences are linear at $T < T_c/2$. The value of the penetration depth $\lambda_{ab}(0)$ changes from 0.15 to 0.2 μm with x lowering. Being normalized by its value at zero temperature the imaginary part σ''_{ab} of the complex conductivity exhibits temperature dependence which is very close to the one for clean superconductor with $d_{x^2-y^2}$-wave $\Delta(\mathbf{k})$ symmetry (solid line in the inset in Fig. 1) and does not change significantly with x. For the cases of optimal doping and so-called $60K$-phase $\sigma''_{ab}(T)/\sigma''_{ab}(0)$ dependences are shown in the inset in Fig. 1.

In Fig. 2 we demonstrate temperature dependences of the c-axis impedance components R_c and X_c. For optimal doping level both the components are linear at $T < T_c/2$ and $\sigma''_c(T)/\sigma''_c(0)$ curve is almost identical to $\sigma''_{ab}(T)/\sigma''_{ab}(0)$. Lowering of the oxygen content leads to the appearance of power law terms in both $R_c(T)$ and $X_c(T)$. In particular, $\Delta X_c(T) = \omega\mu_0\Delta\lambda_c(T)$ curve may be well fitted by T^2 dependence at $T < 25$K in the

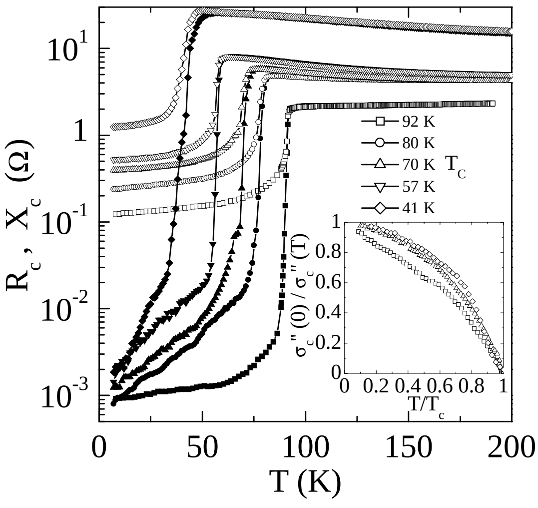

Fig. 2. Real $R_c(T)$ (solid symbols) and imaginary $X_c(T)$ (open symbols) parts of the c-axis surface impedance of $YBa_2Cu_3O_x$ single crystal. Inset shows $\sigma''_c(T)/\sigma''_c(0)$ dependences for the cases of $T_c = 92$, 70 and 41K.

case of $T_c = 41$K. Extrapolation to zero temperature gives the values of $\lambda_c(0)$ approximately 1.5, 3, 5, 7 and 16 μm for $T_c = 92$, 80, 70, 57 and 41 K respectively. The ac-susceptibility measurements of $\lambda_c(0)$ confirmed the microwave ones within the accuracy of the former.

In conclusion, we have presented for the first time the evolution of both Z_{ab} and Z_c temperature dependences of high quality $YBa_2Cu_3O_x$ single crystals grown in $BaZrO_3$ crucibles in a wide range of oxygen content x. At optimal doping level all the surface impedance tensor components proved to be linear at $T < T_c/2$. While $R_{ab}(T)$ and $X_{ab}(T)$ remain linear at low temperatures with x lowering, both $R_c(T)$ and $X_c(T)$ become curved that reflects, seemingly, the reduction of the coupling between CuO_2 layers.

Acknowledgements

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