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Time-domain Terahertz spectroscopy as a diagnostic tool for the electrodynamic properties of high temperature superconductors

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Time-domain Terahertz transmission spectroscopy (TDTTS) has proved to be a unique method for the experimental study of electromagnetic properties of high temperature superconducting thin-films at THz-frequencies in basic and applied research. We have improved the analysis of TDTTS-measurements by numerically extracting the complex index of refraction from the measured complex transmission of the superconducting thin film. Based on this other important figures as surface resistance and dielectric function are derived. We have applied this method to study the surface resistance and the dielectric function of $YBa_2Cu_3O_x$ thin films between 10K and 120K in the frequency range between 0.15THz and 2.4THz. The temperature and frequency dependence of our surface resistance data is successfully explained by a weak coupling model of d-wave superconductivity which incorporates inelastic and elastic scattering at temperatures above 50K. At lower temperatures a deviation of the experimental data from theory is observed which is due to a resonance of the dielectric function.

1. INTRODUCTION

We have investigated two 80nm thin c-axis oriented epitaxial $YBa_2Cu_3O_x$ thin films which have been deposited by laser ablation [1] on a <001> oriented MgO substrate (10x10x1)mm^3 in size. The superconducting transition temperature of the samples are T_C=85K. The $YBa_2Cu_3O_x$ thin films exhibit a high degree of the c-axis orientation δ_C=91% and an oxygen content x=6.95±0.05. The dominating defect in our samples are grain boundaries with grain size lg=2μm [2].

2. EXPERIMENT

Between 0.15THz and 2.4THz the electrodynamic properties of the $YBa_2Cu_3O_x$ thin films have been experimentally determined by time-domain THz-transmission spectroscopy (TDTTS) [2,3]. TDTTS measures in the time-domain the transmission of a picosecond electromagnetic transient through the superconducting film $E^F(t)$ and through the bare substrate $E^S(t)$ as a reference. The Fourier components of the transmitted $E^F(\omega,T)$ and reference $E^S(\omega,T)$ THz-electric fields are obtained through fast Fourier transformation. They define the transmission as $t(\omega,T)= E^F(\omega,T)/E^S(\omega,T)$. The complex index of refraction of the superconducting thin film $n_2=n+ik$ is related to the complex transmission $t(\omega,T)$ through eq.(1) [4]. In this equation d is the thickness of the superconducting thin film, c is the velocity of light, n_3 is the index of refraction of the substrate and $\omega=2\pi f$ the frequency. In our analysis the complex index of refraction of the superconducting thin film $n_2=n+ik$ is determined by numerically solving eq.(1). Then the dielectric function ε and the conductivity σ are calculated by dielectric conversion as $n_2^2=\varepsilon'+i\varepsilon''$ and as $i\omega\varepsilon_0\varepsilon=\sigma'-i\sigma''$. Finally, the surface resistance R_S is determined from the real and imaginary part of the dynamic conductivity $\sigma=\sigma'-i\sigma''$ as $R_S(\omega,T)=((\mu_0\omega/2)(|\sigma|(\omega,T)\sigma''(\omega,T))/(|\sigma|^2))^{1/2}$ [5].

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As demonstrated the electrodynamic properties of superconducting thin films are completely characterized at THz-frequencies by TDTTS. The

$$t(\omega,T)=\frac{E_1^F+iE_2^F}{E_1^S+iE_2^S}$$
$$=\frac{4n_2}{(1+n_2)(n_2+n_3)e^{(-in_2\omega l/c)}+(1-n_2)(n_2-n_3)e^{(in_2\omega l/c)}} \quad (1)$$

advantage of this approach is that only basic electrodynamic relations are involved and no assumptions of the mechanisms of high temperature superconductivity are made.

3. RESULTS AND DISCUSSION

The experimentally determined surface resistance of the $YBa_2Cu_3O_x$ thin films as a function of temperature and frequency is displayed in fig.1. The temperature dependence of the surface resistance is described theoretically by a weak coupling model of d-wave superconductivity. This theoretical description incorporates the d-wave symmetry of the order parameter $\Phi=\Delta_0\cos2\phi$ as well as elastic and inelastic scattering. The lines in Fig.1 are fits of this theory to the measured surface resistance. The details of the calculations are explained in [2,6]. The comparison of experiment and theory exhibits an excellent agreement between 50K and 120K for all frequencies. For f=2THz the agreement of experimental data and theory extends down to T=15K.

A deviation from the theoretically predicted surface resistance is observed for f=1.0THz and f=0.5THz at T<50K. This deviation is due to a resonance in the dielectric function (fig.2) which can be described by a Lorentz oscillator with $\tau=1.6\times10^{-12}$s, $A_1=5577$ and $A_2=4.3\times10^{18}\text{s}^{-1}$ (eq.2).

$$\varepsilon'=A_1+A_2\left(\frac{\tau}{4\pi}\frac{2\pi\tau(f-f_0)}{1+(2\pi\tau(f-f_0))^2}\right)...\varepsilon''=A_1+A_2\left(\frac{\tau}{4\pi}\frac{1}{1+(2\pi\tau(f-f_0))^2}\right) \quad (2)$$

Above 0.5THz the frequency dependence of the dielectric function $i\omega\varepsilon_0\varepsilon=\sigma'-i\sigma''$agrees with the generalized 2-fluid model $\sigma=\sigma_0/(1-i\omega\tau_D)+1/(i\omega\mu_0\lambda^2)$ with $\sigma_0=3000$S/cm, $\tau_D=1\times10^{-13}$s and $\lambda=150.7$nm.

The origin of this excitation is not yet understood and still under investigation. An explanation of the resonance is possibly the excitation of a Josephson plasma resonance. Experimental evidence of such a phenomena in $YBa_2Cu_3O_x$ thin films has been reported [7] previously.

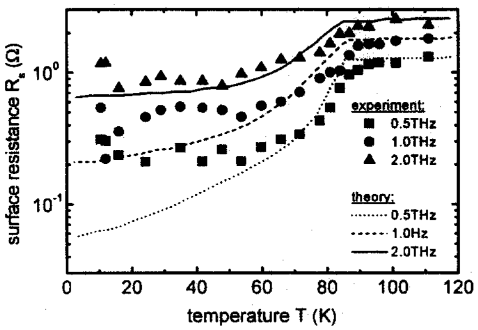

Fig.1 Surface resistance of $YBa_2Cu_3O_x$ thin films at THz-frequencies.

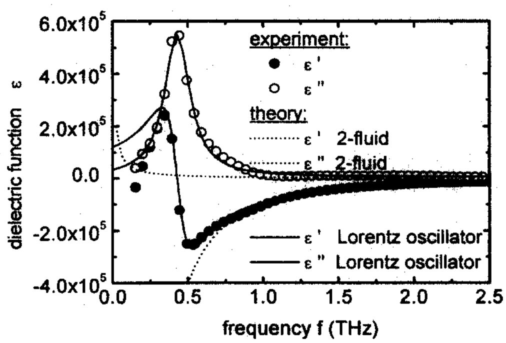

Fig.2 Real ε' and imaginary part ε'' of $YBa_2Cu_3O_x$ thin films as a function of frequency at T=12K.

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