Ca Doped YBCO Films in THz Frequency range

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Abstract. Ca doped YBaCuO thin films were investigated using frequency and time domain THz spectroscopy. A non-monotonic behavior was observed in with a maximum at about 1.8 meV and 1.2 meV depending on Ca concentration. Two batches of thin films 500-600Å thick where used; one of 5% and the other of 10% Ca concentration. The films show a clear c-axis orientation, and 77K for the 5% Ca and 10% Ca respectively. Both thin film batches show a decrease in plasma frequency as temperature increases and superconducting transition is approached. The quasiparticles scattering rate decreases in the normal state and drops when Tc is approached. The imaginary part of the conductivity was found to be proportional to 1/ω, known from the delta-function response.

1. Introduction

Since the discovery of high-Tc superconductors, the pairing mechanism is most interesting issue addressed. The symmetry of the order parameter plays a crucial role in the pairing mechanism. Many experiments have addressed this issue. For hole-doped high-Tc superconductors at the optimal doping, it is well established that the pairing states have dxy - wave symmetry. But the symmetry of the order parameter appears to change with carrier doping. Such a change in symmetry has been suggested by many reports, see for instance [1-5].

Another important question is whether the additional component of the order parameter occurs only on the surface or is in fact a bulk property [6]. While a surface-associated imaginary component would
still be compatible with a pure $d_{x^2-y^2}$ wave bulk order parameter, a bulk-associated imaginary component would not.

In the present work, we apply frequency domain and time domain THz spectroscopy to evaluate the complex conductivity of 50-60 nm thick, c-axis oriented, Ca doped YBa$_2$Cu$_3$O$_{7-\delta}$ (Ca-YBCO) films. These methods assist us in exploring whether there is any indication of an extra order parameter component in the overdoped regime of the mentioned superconductors.

2. Experimental

Samples of 5% and 10% Ca doped YBCO thin films were measured using a quasi optical system in the sub-millimeter frequency domain 2-42 cm$^{-1}$ and in a similar frequency range using the TeraView time domain spectrometer.

Each sample was measured in the temperature range of 20 - 300K in steps of approximately 5 K. Absolute transmission and phase shift were obtained for each sample in the frequency domain using 4 different BWO sources while in the TeraView, time domain spectrometer, a complex transmission function was obtained directly.

The data obtained by both techniques was analyzed in the frequency domain. For each data point analysis we have used a two-layered sample taking into account the dielectric function of the substrate. For the superconducting film we have used the two fluids model assuming frequency independent scattering rate and plasma frequencies for the normal and superconducting part of carriers. In addition we have solved the Fresnel equations for the two-layered model in order to obtain the real part and imaginary part of the conductivity.

The films were deposited by off-axis DC sputtering on LaAlO$_3$ substrate. These are twinned films which reveal a clear c-axis orientation. The phase transition was measured with resistivity and inductance methods. It showed typical values of $T_c$ for the 5% Ca and $T_c$ for 10% Ca.

3. Results and discussion

The complex transmission data obtained by the two sub-millimeter quasi-optical methods for the two layer sample, of thin film and substrate, and have been analyzed to obtain the complex conductivity of the thin film. The complex refractive index of the substrate is well known from previous measurements using the same methods.

The decrease of the scattering rate as a function of temperature is shown in fig. 1 for several Ca doped YBCO samples, the scattering rate saturates at lower temperatures as expected and observed for high quality YBCO thin films and single crystals [2, 3]. Below $T_c$ there is a significant change in the real part of the conductivity which is related to the sharp decrease in the scattering rate of the quasi particles. Fig. 1 also shows that the scattering rate saturates at a higher value for the 10% Ca doped samples as expected.
Scattering Rate (cm$^{-1}$) vs. Temperature (K) for YBCO films.

**Figure 1.** Quasi particles scattering rate as a function of temperature for 10% and 5% Ca doped YBCO. The upper curves at the low temperature represent the 5% Ca doped films.

Fig. 2 shows the plasma frequency in the superconducting state as a function of temperature. It is clearly seen that the 10% Ca doped samples have a higher plasma frequency for $T << T_c$. The higher plasma frequency is consistent with the larger hole-doping of these samples.

**Figure 2.** Superconducting plasma frequency as a function of temperature for the three measured overdoped films containing 5% and 10% of Ca.

Fig. 3 shows the real part of conductivity, $\sigma_1(\omega)$, for a 10% Ca doped sample as a function of frequency for several temperatures above and below $T_c$. Above $T_c$ the conductivity, in our frequency range, increases as temperature decreases. This increase in conductivity is due to the decrease in the scattering rate of the quasi-particles. As can be seen, the conductivity in the normal state is almost frequency independent. Below $T_c$ we noticed the well known $1/\omega$ dependence of the imaginary part, $\sigma_2(\omega)$, and a large increase in the real part, $\sigma_1(\omega)$, due to the appearance of superconducting carriers and the sharp decrease in scattering rate.

Examining $\sigma_1(T)$ for a given frequency we obtain the well known peak at approximately 50K indicating high quality films. The most unusual behavior can be seen in $\sigma_1(\omega)$ below $T_c$. Our data show a non-monotonic frequency dependence of $\sigma_1(\omega)$ with a maximum at about 10 cm$^{-1}$ for the 10% Ca doped samples.
doped films. Similar behavior was obtained with the time domain method and will be reported elsewhere [7]. This non-monotonic behavior observed for several Ca overdoped YBCO films with the two different THz methods is inconsistent with other reports showing the well known Drude-like peak at low temperatures for optimally doped samples [8,9,10,11]. This non-monotonic frequency dependence of $\sigma_1(\omega)$ shifts to higher frequencies and having a maximum at about 15 cm$^{-1}$ for the lower doped films with 5% Ca, i.e. lower hole-concentration, shown in fig. 4. These maximum values for both measurements can be related to an energy sub-gap, $2\Delta$, of about 1.8 meV and 1.2 meV for the 10% and 5% Ca doped films respectively.

Figure 3. The real part of conductivity as a function of frequency, obtained for 10% Ca doped YBCO film.

Figure 4. The real part of conductivity as a function of frequency, obtained for 5% Ca doped YBCO film.

In conclusion non-monotonic behavior of $\sigma_1(\omega)$ was observed for two batches of 5% and 10% Ca overdoped YBCO thin films applying two independent THz methods. Both methods yielded similar results. The observed maximum in the real part of conductivity was at smaller energy in comparison to previously reported data using bulk-sensitive microwave penetration depth and surface-sensitive tunneling measurements. The mentioned maxima values decrease as temperature increases. The larger maximum in $\sigma_1(\omega)$ observed for the 5% Ca doped samples is consistent with their smaller scattering rate. The larger energy maximum for $\sigma_1(\omega)$ observed for 5% Ca doped samples is inconsistent with their larger plasma frequency at $T << T_c$ taking into account that this non-monotonic behavior is related to a sub-gap which is doping dependent.

References
[1] T.Masui,M.Limonov,H.Uchiyama,S.Lee,S.Tajima,A.Yamanaka,Phys.Rev.B 68 060506(R) (2003)
[2] E. Farber et al. Europhys. Lett. 67, 834 (2004)
[3] A. Hosseini et al. Phys. Rev. B. 60, 1349 (1999)
[4] R. Beck, Y. Dagan, A. Milner, A. Gerber, G. Deutscher, Phys. Rev. B 69, 144506 (2004)
[5] H.J.H. Smilde, A.A. Golubov, G. Ariando, G. Rijnders, J.M. Dekkers, S. Harkema, D.H.A. Blank, H. Rogalla, H. Hilgenkamp, Phys. Rev. Lett. 95, 257001 (2005).
[6] Y. Dagan and G. Deutscher, Europhys. Lett. 57, 444 (2002)
[7] N. Bachar et al, will be submitted to Physical Review B (2011)
[8] J.M. Chwalek, J.F. Whitaker, G.A. Mourou, Electronics Letters, 27, 447 (1991)
[9] A. Frenkel, F. Gao, Y. Liu, J.F. Whitaker, C. Uher, S.Y. Hou, J.M. Phillips, Physical Review B, 54, 1355 (1996)
[10] Toshihiko Kiwa, Masayoshi Tonouchi, Physica C: Superconductivity, 362, 314 (September 2001)
[11] Tsong-Ru Tsai, Cheng-Chung Chi, Sheng-Fu Horng, Physica C: Superconductivity, 391, 281 (September 2003)