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Josephson plasma oscillations in $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_4$.

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We present new data on the *c*-axis far infrared reflection spectrum of $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_4$. The observed reflectance edge below T_c is interpreted in a Josephson plasma oscillation model, which provides a novel spectroscopic way to determine the critical current density. Furthermore, we show that the presence of a small absorption peak near the zero crossing of the dielectric function can be explained in an effective medium calculation.

Introduction

The magnitude and nature of the coupling between the CuO_2 layers in the high- T_c materials is of prime importance for the understanding of the anisotropic superconductive properties, and possibly also for the underlying mechanism for superconductivity. Direct observation of Josephson like interplane coupling in several different high- T_c compounds with double and triple CuO_2 layers, was reported in the work by Kleiner *et al.*[1]. In this contribution we show that the observed reflectance edge in the *c*-axis optical response of $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_4$ can be understood in terms of a simple Josephson model in which the sample is treated as a stack of superconducting sheets, separated by dielectric barriers. The bulk superconductivity and coherent *c*-axis transport is then induced by the Josephson coupling between the layers. For such a layered system with characteristic (tunneling) conductance σ_n and capacitance C , we can write the total current as [2]:

$$j_t = j_c \sin \phi + C \frac{dV}{dt} + V \sigma_n, \quad (1)$$

where the terms on the right correspond to the Josephson current, the displacement current and the quasiparticle current, respectively. Assuming that the phase variations are small, the following dielectric function can be derived:

$$\epsilon = \epsilon_0 \left(1 - \frac{\omega_p^2}{\omega^2} + \frac{i\gamma}{\omega} \right) \quad (2)$$

where $\omega_p = \sqrt{2ej_c/\hbar C}$ is the Josephson plasma frequency, and the damping $\gamma = \sigma_n/C$. This equation shows that no radiation can penetrate the sample at frequencies below ω_p . From the expression for ω_p one can deduce directly the critical current density, which provides an alternative (spectroscopic) method of determining j_c . An advantage of this approach is that the electromagnetic field probes the bulk properties of the sample at near equilibrium conditions and at very low effective current densities.

Results and discussion

Our measurements were done on a single crystal of $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_4$ ($T_c = 34$ K) grown by the travelling solvent floating zone method. Figure 1 shows the *c*-axis reflectance below 80 cm^{-1} at various temperatures between 10 K and 36 K. The data confirm the previous results of Tamasaku *et al.*[3]. Above T_c the spectrum resembles that of an insulator whereas below T_c a weakly damped plasma edge appears. The inset of fig. 1 shows the deduced j_c versus temperature as dots. The only unknown parameter in the conversion from ω_p to j_c is the capacitance, which we calculated from the measured dielectric function. The absolute value of j_c at low temperature is larger than e.g. the magnetization measurements of Ref. 4 by roughly a factor of 10. This can be related to the fact that the infrared response is a more intrinsic way of probing the bulk criti-

Figure 1. Reflectance of $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_4$ at various temperatures between 36 K and 10 K. The inset shows the deduced temperature dependence of the critical current (dots) along with a BCS based theoretical prediction.

cal current. The solid line represents the functional dependence of j_c on temperature using the Ambegaokar-Baratoff (AB) expression for a BCS gap $\Delta(T)$. The absolute value of the measured j_c agrees well with the AB result and the optically determined $\sigma_n = 8 \Omega^{-1}\text{cm}^{-1}$.

The feature which appears in R just above the plasma frequency gives rise to a small peak in the conductivity which is also visible in Tamasaku's data. This peak shifts to lower frequencies when the temperature is increased and closely follows the position of the plasma edge. The origin of this feature is related to the fact that when, the real part of the dielectric function is close to one, the sample is effectively transparent. Any residual absorption is therefore more easily detected around this frequency. Figure 2 shows the data at 10 K together with a fit according to Eq. 2. (dashed line). The solid line represents an effective medium calculation for the same model, but now with a volume fraction of 10 % non-superconducting spherical inclusions. The conductivity of the normal inclusions was assumed to be Drude-like, described by a low plasma frequency of 215 cm^{-1} , a relaxation rate of 4 cm^{-1} and an ϵ_0 of 8. The correspondence between fit and experimental data is quite clear. The 10 % volume fraction of non-superconducting mate-

Figure 2. Reflectance at 10 Kelvin (small dots) together with a bare plasma fit (dashed line) and a fit (solid line) assuming 10 % normal inclusions in the sample. The inset shows the corresponding conductivity.

rial is much larger than expected from crystallographic data and microprobe analysis of the sample. This indicates that the defects probably have a more extended character.

Conclusions

In conclusion, we presented detailed c -axis reflectivity data on $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_4$. Using a simple Josephson model we obtain a good quantitative description of the observed plasma edge. Details of the spectrum near the zero crossing of ϵ' can be explained by taking into account a small fraction of normal inclusions in the sample.

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