Original contributions

Determination of the gap distribution in YBa$_2$Cu$_3$O$_7$
using a far-infrared reflection-Fabry-Pérot device

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Abstract. This paper reports on far-infrared measurements of YBa$_2$Cu$_3$O$_7$ films oriented with the c-axis perpendicular to the surface, by using a silicon reflection Fabry-Pérot interferometer as a multireflection device. From these we could derive the dielectric function, the refractive index, the field penetration depth and the surface impedance of the material. The one order of magnitude higher sensitivity of the method compared to a direct reflectance measurement allowed to find an almost continuous gap distribution in the 70-215 cm$^{-1}$ region together with a separate gap at about 330 cm$^{-1}$. A quasi-zero gap absorption is found down to 20 cm$^{-1}$ even at low temperatures (10 K).

1. Introduction

Many efforts with various methods have been applied since the discovery of the high-$T_C$ cuprates [1] in locating superconducting energy gaps. An excellent and critical review of investigations concerning these gaps with special emphasis on the tunneling measurements was given in [2]. We concentrate here on far-infrared techniques and on the YBa$_2$Cu$_3$O$_7$-compound, the most widely investigated material (see survey articles [3-5]). There is increasing evidence that in this material a gap might exist below the BCS value but also above it [6-9]. The latter, which is located around a frequency of 320-330 cm$^{-1}$, was strongly confirmed by Raman investigations on the shift and change of widths of phonons when approaching and passing the critical temperature $T_C$ from above [10]. Infrared reflectance measurements on untwinned single crystals [11] were interpreted with a still higher gap at about 500 cm$^{-1}$ ($\hbar \omega_c / k T_C \approx 8.00$), but it does not behave BCS-like, since it does not decrease with increasing temperature and is still apparent above $T_C$. The infrared measurements on crystals and on films with the electric field $E$ perpendicular to the c-axis generally suffer under the very high reflection occurring below 500 cm$^{-1}$, which is a consequence of the fact that at low temperature $T$ the scattering rate $\omega_s = \tau^{-1}$ is apparently small as compared to the gap frequencies, i.e. the material is rather close to the clean limit. Only in iron-doped ceramics clear evidence for a sharper gap was found [12, 13] which moves to lower energies with increasing iron concentration in accordance with the theory. However, the spectra of ceramics are severely disturbed by the signature of c-axis phonons so that the interpretation of the results is more difficult. Transmission measurements on oriented films do not help either because the films have to be very thin ($< 30$ nm) and a sufficiently transparent substrate is needed throughout the far infrared.

Considering again the high reflection $R$, one is faced with the experimental problem of measuring it within an absolute accuracy of a small fraction of a percent. Since the necessary reflection standard is normally not better known than by 0.5% in $R$ and the replacement of the sample by a reference mirror yields additional errors, it seems hopeless to improve the method for a single reflection in the far infrared. A similar situation as for the high $T_C$ superconductors occurs for the heavy fermion metals in that spectral range where the heavy carrier mass is essential. Therefore, multiple reflection techniques, adapted to the limited size of the specimens, should be used. Such techniques have already been applied before [14, 15].

In this paper we describe measurements on YBa$_2$Cu$_3$O$_7$ films with $E \perp c$ by using a Si-reflection Fabry-Pérot (RFP) in the 20-650 cm$^{-1}$ spectral range. In preliminary publications [16, 17] we have presented first results. In this investigation we describe the method in more quantitative detail and show how to extract useful information from the Fabry-Pérot resonances, especially those concerning the superconducting gaps.

2. Experimental and results

Our system is made up of a sandwich, whose components are of a silicon wafer (approximately 200-300 μm in
Fig. 1. The reflection Fabry-Perot (RFP) sandwich with the Si-wafer (refractive index \( n \) and thickness \( d \)) and the opaque superconducting film (with refractive index \( \hat{n} \), and the \( c \)-axis perpendicular to the surface) behind it. The substrate of the film has been omitted here. The reflection amplitudes \( r_i, r_{01}, r_{12} \) are explained in the text.

thickness), and a superconducting film which is laser-ablated on a SrTiO\(_3\) substrate. The latter one is pressed onto the Si-wafer, avoiding air spacing (see Fig. 1). The beam inside a Fourier transform spectrometer (FTS, here Bruker FS-113V) is then reflected on this RFP from the Si side. The Fabry-Pérot effect results from the high reflectivity of the superconductor on the one hand, and the more moderate reflectance of the Si itself, on the other. About 86 reflection resonances are then found in the investigated spectral range, which can be sufficiently resolved with a resolution of 0.1 cm\(^{-1}\) of the FTS. An earlier described mesh-reflection Fabry-Pérot [18], developed for FIR laser applications, has much too sharp resonances for FTS. The theory for our RFP is given in detail in the Appendix I.

As customary for an interferometer technique, several requirements are necessary. First, the Si-wafer should be highly plane parallel (better than a few arc sec) and the sample including its substrate must be plane to a small fraction of a \( \mu \)m. Second, the angle of incidence in the spectrometer should be kept as small as possible (\( \sim 11^\circ \) in our case) together with a not too large convergence of the focused beam (opening angle of 9\(^\circ\)). The last two deviations from an ideal collimated beam with vertical incidence are somewhat relaxed by the rather high refractive index of Si. A half-quantitative treatment of all the three effects mentioned above is given in Appendix II.

A result with a rather good superconducting film (\( T_c \approx 90 \) K) and a moderately plane parallel Si-wafer (but very high purity) is shown in Fig. 2. The film had a thickness of about 0.5 \( \mu \)m, sufficient to be opaque throughout our spectral range. In this way we are not bothered by the IR-properties of the SrTiO\(_3\) substrate. The measurements were performed at 10 K and 100 K, with a gold mirror serving as a reference standard which was measured correspondingly on both temperatures.

In principle, it should be possible to get the complex refractive index \( \hat{n} \) of the superconductor at each resonance since we have information from two independent sources, the resonance frequency \( \nu_0 \) and the minimal reflectance \( R_0 \) or maximal absorbance \( A_0 = 1 - R_0 \) (see Appendix I). First results showed that the accuracy to determine \( \nu_0 \) and \( R_0 \) is just good enough to get \( \hat{n} \) within \( \pm 30\% \) in the frequency range between 100 cm\(^{-1}\) and 200 cm\(^{-1}\). But for the higher frequencies the method is hampered by the fact that we have a convergent beam...