Infrared Study of $YBa_2Cu_3O_{7-\delta}$ in High Magnetic Fields

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Abstract. The magnetic-field dependence of the far-Infrared transmittance was measured for $YBa_2Cu_3O_{7-\delta}$ thin films. The measurement was done at 4.2K for $YBa_2Cu_3O_{7-\delta}$ films on both sapphire and MgO substrates. The results show no significant change in the transmittance spectra as the field was applied. This implies very low loss for the vortex state at low temperatures.

Keywords: Infrared, magnetic field, transmittance
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INTRODUCTION

Far-infrared spectroscopy has been widely applied to investigate the vortex dynamics in high T_c superconductors. Karrai *et al.*[1] measured the transmittance of $YBa_2Cu_3O_{7-\delta}$ thin films, finding an increase in transmittance below ~125 cm^{-1} with increasing field. This effect was attributed to dipole transitions associate with bound states in the vortex cores. Measurements of the far-infrared reflectivity *R* of a superconducting $YBa_2Cu_3O_{7-\delta}$ thin film by Eldridge *et al*.[2] found a strong dependence on magnetic field, suggesting that the increase in transmission at low wavenumber in the experiment of Karri *et al.*[1] was mainly due to a decrease in reflectivity. In their experiment they also observed the phonon mode at far-infrared region in the high magnetic field, which is usually not expected in the *ab*-plane films at zero field.

In contrast, Liu *et al.*[3] measured $YBa_2Cu_3O_{7-\delta}$ films at various temperatures in magnetic fields up to 30 T. Their data clearly indicates that at low temperatures (below 50 K) there is no significant field dependence to either reflectance or transmittance. But at higher temperatures, such as 60 K and 72 K, there was a significant increase of the far-infrared transmittance (below ~120 cm-1) with increasing magnetic fields.

EXPERIMENT

We studied superconducting and non-superconducting films on several substrates. The substrates used for the superconducting $YBa_2Cu_3O_{7-\delta}$ films were MgO and sapphire, with a CeO buffer layer. The films are about 400 Å in thickness, with T_c around 85-90 K. A non-superconducting $YBa_2Cu_3O_{6+x}$ film on silicon was also studied.

Our far-infrared transmittance measurements were done at the National High Magnetic Field Laboratory, Tallahassee FL. The experiment used a Bruker 113v spectrometer and light pipe in conjunction with an 18-Tesla superconducting magnet.[4] The sample insert allowed exchange of sample and reference, so that absolute transmittance measurements could be made.

RESULTS

The transmittance spectra of the films taken at 4.2 K at different magnetic fields are shown in Fig. 1. We observed practically no influence of the magnetic field on the far infrared transmittance spectra of any of the films. The noise around 140 and 230 cm^{-1} is due to poor beam-splitter efficiency at these frequencies. Outside of these two regions, the variation in transmission with field is $\Delta T/T < \pm 8\%$, set by the signal to noise ratio in the data. Moreover, note that for the two superconducting samples (Fig. 1, panels a and b) the low frequency transmittance tends to zero, as expected for a sample where the far infrared properties are dominated by the inductive response (σ_2). Were the loss (σ_1) significant, there would be finite transmittance at low frequencies. Thus, we can conclude that with the external field perpendicular to the superconducting $YBa_2Cu_3O_{7-\delta}$ film, no far-infrared

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magnetoresistance was detected at 4.2 K and in the high field regime. The non-superconducting sample (Fig. 1, panel c) also showed no field-dependent absorption. (The oscillations in this sample are due to multiple internal reflections in the Si substrate.)

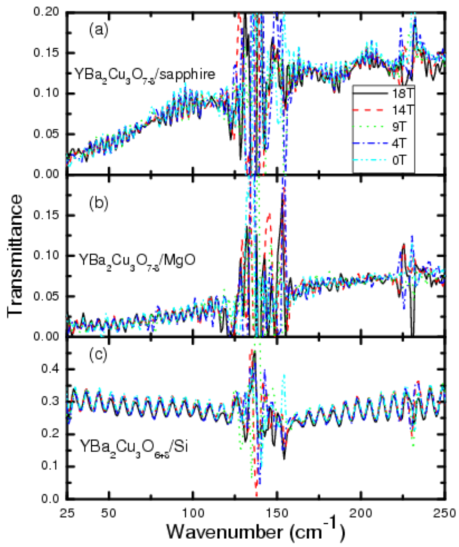

FIGURE 1. At 4.2 K, transmittance of samples at different magnetic fields.

DISCUSSION

Because our infrared electric field is parallel to the *ab* plane, the vortices oscillate within their pinning potential. We model the vortex state as a parallel mixture of vortex cores (normal state) surrounded by superconductor. The fractional area of the cores is $H/H_{c2}(T)$ with H_{c2} the upper critical field. The dielectric function of this model is:

$$\varepsilon(\omega) = -\frac{\omega_{ps}^2}{\omega(\omega+i0^+)}\left[1-\frac{H}{H_{c2}}\right] - \frac{\omega_{ps}^2}{\omega(\omega+i/\tau_s)}\left[\frac{H}{H_{c2}}\right] + \varepsilon_{ir} \qquad (1)$$

Where ω_{ps} is the superfluid plasma frequency, $1/\tau_s$ is the damping constant inside the vortex, and ε_{ir} is the non-superconductor part of the dielectric function. (A more complete model would include a normal fluid, midinfrared absorption, and high-frequency processes. Here, these are all lumped into ε_{ir}.)

In order to explain the absence of changes in our optical spectrum, consider the change of optical conductivity σ as the vortex density is increased: $\sigma_s(\omega)=\omega_{ps}^2[1-H/H_{c2}]/4\pi i\omega$; $\sigma_n(\omega)=\omega_{ps}^2[H/H_{c2}]S(\omega)/4\pi$. Here, $S(\omega)$ is the frequency dependence of the vortex conductivity and is initially dominated by $1/(i\omega - 1/\tau_s)$. The change in $\sigma(\omega)$ due to a conversion of super to normal fluid is given by $\Delta\sigma(\omega) = \omega_{ps}^2 (H/H_{c2})[S(\omega) - i/\omega]/4\pi$. Specifically, $\Delta\sigma(\omega)$ is maximum at zero frequency and decreases rapidly with frequency for $\omega > 1/\tau_s$. In our experiment, the measurements are limited to $\omega > 25\ cm^{-1}$ and the quasi-particle scattering rate $1/\tau_s$ of our films is very small. Moreover, the change in $\Delta\sigma(\omega)$ is expected to be not big for fields up to our maximum field of 18 T when H_{c2} is about 240 T. Thus, it is possible that any change in the spectra should be relatively small in our far-infrared frequency and magnetic field range.

CONCLUSION

The transmittances of $YBa_2Cu_3O_{7-\delta}$ films with different substrate were measured at 4.2 K in the high magnetic field up to 18 T. The transmittance spectra did not show significant changes with the changing of the magnetic field. This result may indicate a very low loss for the vortex state at low temperature.

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