Optical properties of thin $YBa_2Cu_3O_7$ films in the IR region

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The IR reflection spectra of superconducting $YBa_2Cu_3O_{7-\delta}$ films deposited on substrates of various materials have been studied. The value of the parameter $2\Delta/kT_c$ found from the experimental results is about 9.5.

The method of magnetron sputtering has been used to study the IR reflection of thin $YBa_2Cu_3O_{7-\delta}$ films deposited on substrates of polycrystalline Al_2O_3 and single crystals of $SrTiO_3$, ZrO_2, and MgO. The dc conductivity reveals a sharp superconducting transition 1.5–2 K wide at $T_c = 84$ K for the films on the $SrTiO_3$ and ZrO_2

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substrates and at $T_c = 78$ K for the films on the MgO substrate. The film deposited on the Al_2O_3 substrate exhibits a wide transition, which begins at 80 K and ends at 60 K. In all of the films, the resistance is a linear function of the temperature in the normal phase.

The temperature dependence of the reflection spectra of the films with respect to that of a silver comparison standard was measured on an AFS-01 Fourier spectrometer with the help of a cooled reflection attachment at an angle of incidence of 45°. The sample temperature was regulated within 0.2 K. The spectra were recorded at a resolution of 1.9 cm^{-1}; the error in the determination of the reflection coefficient did not exceed 1%.

Figure 1 illustrates the results with the reflection spectrum at 4.2 K of a $YBa_2Cu_3O_{7-\delta}$ film with a thickness of 1500 Å on a $SrTiO_3$ substrate. Also shown here is the reflection spectrum of the substrate at 4.2 K. It can be seen from Fig. 1 that the film is semitransparent, since its reflection spectrum has structural features associated with the selective reflection of the substrate in the residual-ray region. We should point out that the reflection spectra of the other films of the same thickness also exhibit structural features associated with the reflection of the substrate.

The spectra of all the films except that deposited on the MgO (Figs. 2 and 3) clearly reveal a reflection maximum at 570 cm^{-1}, which is also observed in the spectra of ceramics and is due to a phonon mode which results from the vibrations of Cu-O bonds along the c axis.[1] The spectrum of the film on ZrO_2 (Fig. 3) also has reflection maxima at 150, 280, and 320 cm^{-1}, of which only that at 320 cm^{-1} is seen in the spectrum of the film on the $SrTiO_3$ substrate. These maxima correlate well with structural features in the IR and Raman spectra of the ceramics[1,2] and appear to stem from the vibrations of Ba-O and Cu-O bonds in the ab plane. All of these structural features are also present in the spectra of the films deposited on the Al_2O_3, but they are not observed in the spectra of the films on the MgO substrate.

The data from an x-ray structural analysis of a film on a $SrTiO_3$ substrate indicate that the film is a single crystal, with c axis directed essentially normal to the surface of the substrate. The presence of phonon structure in the spectra of the films deposited on

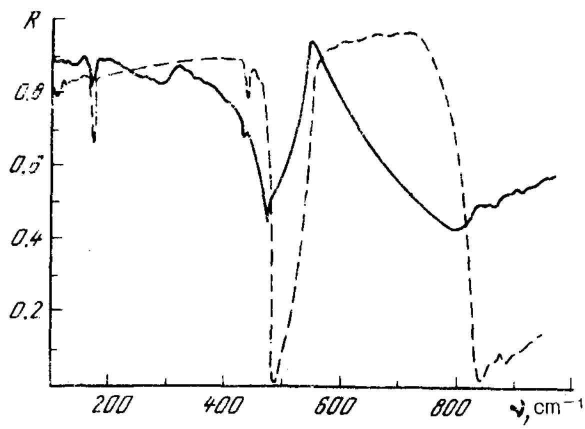

FIG. 1. Reflection spectra at 4.2 K of a $YBa_2Cu_3O_{7-\delta}$ film (solid line) and of the $SrTiO_3$ substrate (dashed line).

the ZrO_2 and Al_2O_3 can apparently be explained on the basis that on these substrates, in contrast with $SrTiO_3$ and MgO, it is not possible to grow epitaxial films, and the reflection of the IR light is from disoriented single-crystal regions in which the c axis deviates from the normal to the surface of the substrate.

Shown at the top in Figs. 2 and 3 are spectra of the ratio of the reflection coefficients of the films on the $SrTiO_3$ and ZrO_2 substrates in the superconducting and normal states. We see that there are two spectral regions with $R_S/R_N > 1$: from 80 to 450–500 cm^{-1}, without a clearly expressed maximum (nor is there a crossing $R_S = R_N$ in the long-part of the spectrum), amd from 500–520 cm^{-1} to 650–700 cm^{-1}. The reflection coefficients of the films on the Al_2O_3 and MgO substrates in the superconducting state are higher than that of the films in the normal state over the entire spectral region studied, from 80 to 1000 cm^{-1}. There are no structural features on the frequency dependence of R_S/R_N. As the temperature is varied, we observe no significant frequency shift of the maximum at 550 cm^{-1}, but for all of the films an increase in the temperature to T_c causes the reflection coefficient R_S to approach R_N in such a way that the frequency dependence of R_S/R_N disappears, and we have $(R_S/R_N) \sim 1$ over the entire region studied. The R_N spectra were recorded at 92–93 K. Increasing the temperature further, from 93 K to 150 K, did not alter the results.

Under the assumption that the maximum of R_S/R_N at 550 cm^{-1} seen in the spectra of the films on the $SrTiO_3$ and ZrO_2 substrates is due to an absorption of IR light during the excitation of charge carriers across the superconducting gap,[3,4] we find the value 9.5 ± 0.5 for the parameter $2\Delta/kT_c$ of the $YBa_2Cu_3O_{7-\delta}$ films.

We observed a corresponding maximum on the frequency dependence of R_S/R_N for one of the ceramic $YBa_2Cu_3O_{7-\delta}$ samples with $T_c = 93$ K at 540 cm^{-1}. In addi-

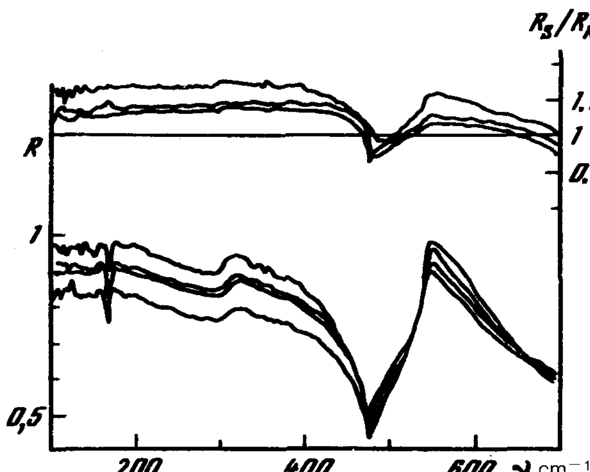

FIG. 2. Reflection spectra of a $YBa_2Cu_3O_{7-\delta}$ film on a $SrTiO_3$ substrate at various temperatures. From top to bottom: $T = 4.2$ K, $T = 28$ K, $T = 70$ K, and $T = 92$ K. Shown at the top is the frequency dependence of the ratio R_S/R_N. The value of R_N was measured at $T = 4.2$ K. From top to bottom; $T = 4.2$ K, $T = 28$ K, $T = 70$ K.

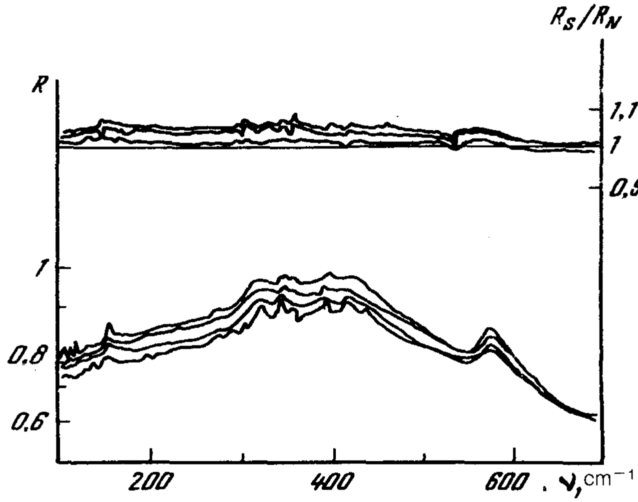

FIG. 3. Reflection spectra of a $YBa_2Cu_3O_{7-\delta}$ film on a ZrO_2 substrate at various temperatures. From top to bottom: $T = 4.2$ K, $T = 29$ K, $T = 57$ K, and $T = 93$ K. Shown at the top is the frequency dependence of the ratio R_S/R_N. The value of R_N was measured at 93 K. From top to bottom: $T = 4.2$ K, $T = 29$ K, $T = 57$ K.

tion to this maximum, we also observed maxima at 180 and 320 cm^{-1}, which have been mentioned previously.[5] In contrast with the data of Ref. 5, however, none of the R_S/R_N maxima which we observed undergo a shift along the frequency scale as the temperature is raised to T_c. An estimate of the parameter $2\Delta/kT_c$ for this case yields 8.2 ± 0.5 in good agreement with the data of Ref. 6, where the value $2\Delta/kT_c = 8$ was reported for a single crystal.

The value which we found from the IR reflection of the films for the parameter $2\Delta/kT_c$ is greater than the value of $2\Delta/kT_c$ found by other methods[7,8] for $YBa_2Cu_3O_7$ films: 3.5 and 4.5, respectively. However, the values which we found do not exceed the theoretically possible upper limit $2\Delta/kT_c = 11$ for the case of an extremely strong electron-phonon coupling.[9]

The results of our optical study of thin $YBa_2Cu_3O_{7-\delta}$ films yield an estimate of the depth to which the IR light penetrates into the superconductor. As we mentioned earlier, the films with a thickness of 1500 Å are semitransparent in the region 100–600 cm^{-1}, since phonon peaks of the substrates are observed in their reflection spectra. The reflection spectrum of a film 2700 Å thick on a $SrTiO_3$ substrate reveals no structural features associated with the selective reflection of the substrate. It can thus be concluded that the depth to which the IR light penetrates into a superconducting film lies between 1500 and 2700 Å.

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