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Study of the energy gap in thin films of a high-T_c superconductor

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(Submitted 23 November 1988)
Pis'ma Zh. Eksp. Teor. Fiz. **49**, No. 1, 23–27 (10 January 1989)

Thin $Y(Ho)Ba_2Cu_3O_{7-x}$ films grown by laser deposition on $SrTiO_3$ substrates were studied by the method of IR reflection spectroscopy. The orientation of the crystallites in the samples is found to have an effect on the reflection spectra and on the temperature dependence of the spectra. For films whose properties are similar to those of single-crystal films the results of low-temperature measurements are in agreement with the corresponding calculations based on the Mattis-Bardeen theory.

We have studied the IR reflection from thin superconducting $Y(Ho)Ba_2Cu_3O_{7-x}$ films which were grown by the method of laser deposition on a strontium titanate substrate. Such a method of growing films allows us to obtain films of various thicknesses and the use of oriented substrates [in particular, $SrTiO_3(100)$] leads to the formation of a film with the preferred orientation of the *ab* plane parallel to the surface of the sample.[1] In this orientation the contribution of the active IR phonons to the reflection spectra decreases appreciably, since in the case of the *ab* plane, with its high dc conductivity, the interaction of light with the crystal lattice is, as follows from the experimental studies of the reflection of single crystals,[2] almost completely screened. The optical measurements of the width of the energy gap 2Δ in this case can be greatly simplified, since the frequency region we are investigating has virtually no phonon structural features which complicate the interpretation of data obtained from ceramic samples.[3,4]

Figure 1a shows the reflection spectrum of a film at $T = 300$ K, whose $\langle c \rangle$ axis is

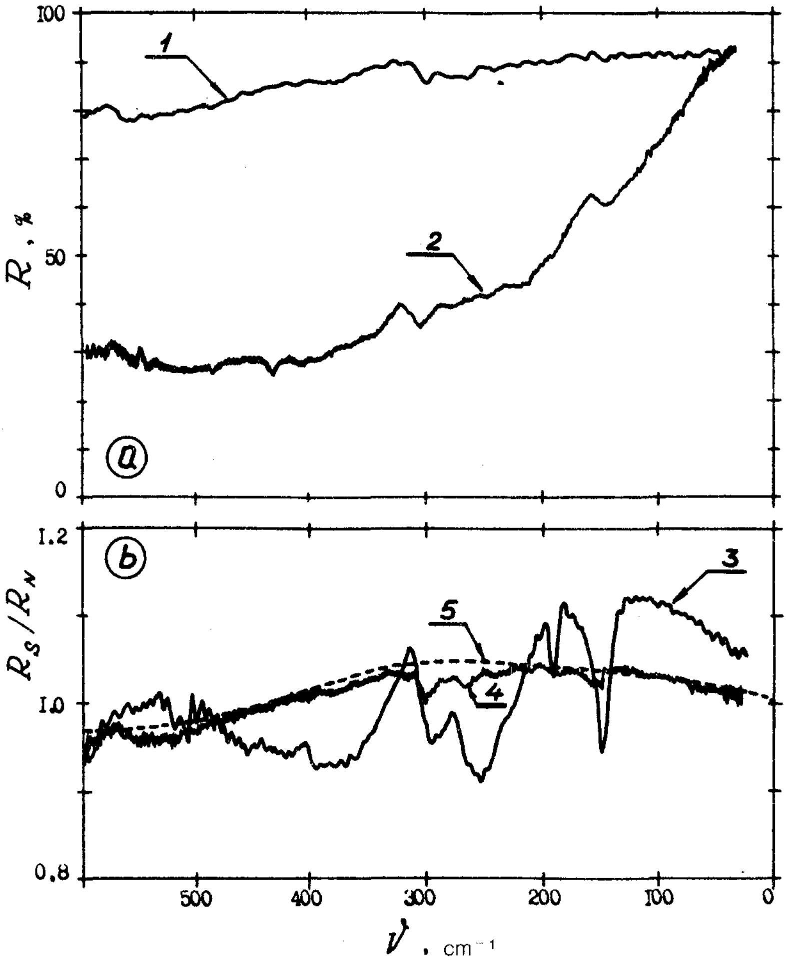

FIG. 1. (a) Reflection spectra; (b) spectral dependence of the ratio R_S/R_N for the compound Y–Ba–Cu–O. Experimental curves: 1—Thin film with the ⟨c⟩ axis running normal to the surface; 2—ceramic with the composition 1:2:3; 3—R_S (Θ) for a ceramic sample at $T = 4$ K, R_N—at $T = 95$ K; 4—R_S for an oriented film at $T = 4$ K, R_N—at $T = 91$ K: 5—calculated R_S curve, taken from Ref. 5, for a film at $T = 0$ K, R_N—at $T = 91$ K, $2\Delta(0) = 270$ cm^{-1}.

oriented perpendicular to the surface of the sample (curve 1). The spectrum is virtually devoid of the phonon lines characteristic of polycrystalline samples (curve 2). The results of low-temperature measurements are shown in Fig. 1b as a frequency dependence of the ratio of the reflection coefficients of the sample in the superconducting state and the normal state, R_S/R_N. We see in Fig. 1 that the plots obtained for the film (curve 4) and for the ceramic (curve 3) differ fundamentally in nature. Furthermore, the experimental spectrum of R_S/R_N conforms well to curve 5, which was calculated on the basis of the Mattis-Bardeen theory.[5] Despite the fact that it is difficult to unambiguously determine the frequency of the maximum on the R_S/R_N curve for a thin-film sample, which corresponds to $2\Delta(0)$, this spectrum can be used to estimate this value within 50 cm^{-1}. Direct measurements of the gap width based on the reflection spectra for the oriented films will then give us the value $2\Delta(0) = 250 \pm 50\ cm^{-1}$, consistent with the data obtained for polycrystalline samples, using a special method of analyzing the measurement results.[6] We can assert, therefore, that the complex nature of the ratio R_S/R_N for ceramics is determined not by a superconductivity mechanism that differs from the BCS mechanism but rather by the presence in these

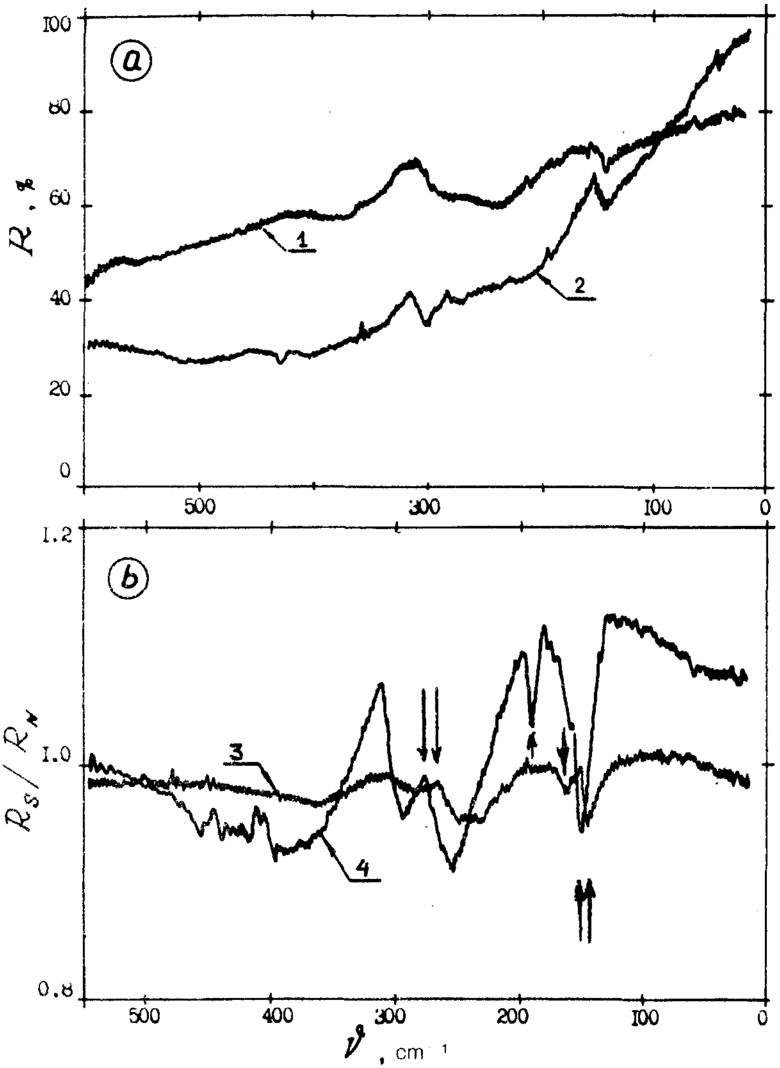

FIG. 2. (a) Reflection spectrum (curve 1) and (b) R_S/R_N spectrum (curve 3) for an Ho–Ba–Cu–O film grown on a block substrate. Similar curves for a Y–Ba–Cu–O ceramic are given for comparison (curves 2 and 4, respectively). R_S was measured at $T = 4$ K and R_N was measured at $T = 95$ K.

systems of anisotropic crystals with different orientations. This assertion is illustrated in Fig. 2, which shows the reflection spectra of the film which consists of blocks with different orientations (because of the block structure of its substrate). It turns out that both the reflection spectrum (curve 1 in Fig. 2) and the R_S/R_N curve (curve 3) for this film are similar to the curves obtained for ceramics (curves 2 and 4, respectively). The only difference that has been observed is the slight difference in the frequencies of the phonon structural features (indicated by arrows) which stems from the replacement of the yttrium ion by holmium in the film.

The orientation of crystals is, however, not the only requirement imposed on the films when the quantity 2Δ is measured directly from the reflection spectra. Appreciable thickness of the film is also a necessary condition because of the deep penetration

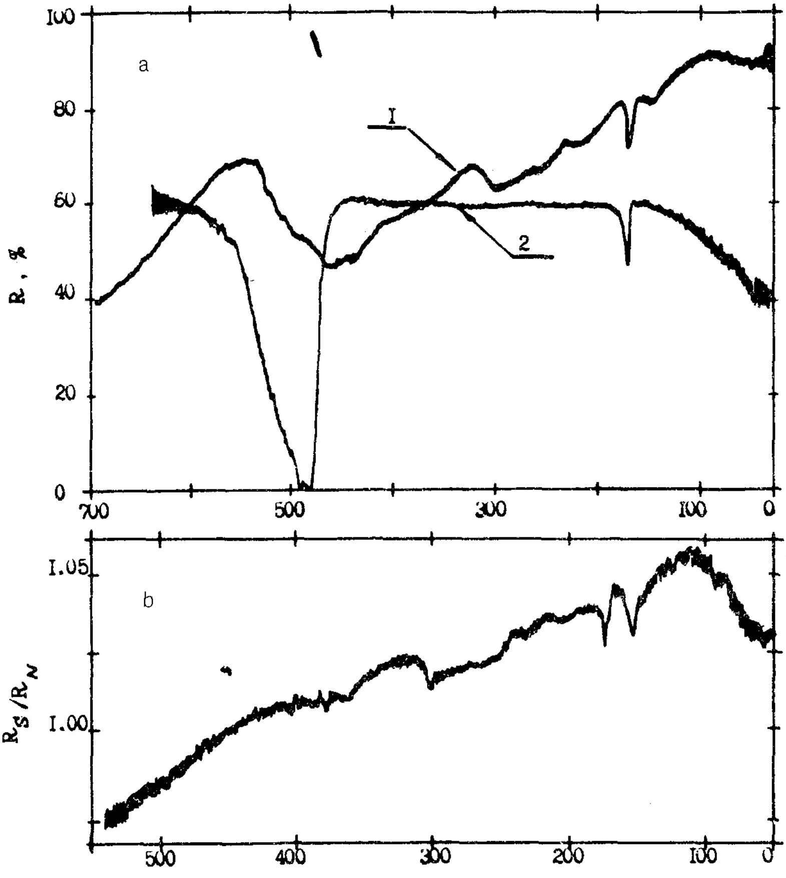

FIG. 3. (a) Reflection spectra and (b) R_S/R_N reflection spectrum for a thin Y-Ba-Cu-O film. The film thickness is 1000 Å; R_S was measured at $T = 4$ K and R_N was measured at $T = 95$ K. Curve 2—Spectrum of the $SrTiO_3$ substrate.

of the IR light into the materials under study, which is generally greater than the average thickness of the oriented films (usually one or two thousand angstroms). Figure 3a shows the reflection spectrum of the oriented 1000-Å-thick film (curve 1). This spectrum clearly shows all the structural features of the phonon spectrum of the $SrTiO_3$ substrate (curve 2). This means that the experimentally detected reflected signal is not the reflection spectrum but is instead a complex combination of reflection from the film and transmission through it which occurs as a result of reflection from the substrate. As the sample undergoes a transition to the superconducting state, the absorption of light near the energy gap approaches zero, causing a change in the relationship between the transmission and reflection. The ratio R_S/R_N acquires a shape illustrated by curve 3 in Fig. 3b. To determine 2Δ from this spectrum, we must calculate from a model the contribution of the energy gap to the redistribution of the reflection and transmission occurring as a result of transition of the material to the superconducting state.

The following conclusions can thus be drawn from the analysis of IR data obtained from thin oriented films whose $\langle c \rangle$ axis runs perpendicular to the surface of the sample:

1. The *ab* plane has a metallic reflection spectrum which corresponds to an appreciable conductivity along the copper-oxygen layers.

2. The phonon structural features in the reflection spectra, observed in ceramics and block films, are attributable to their disorientation.

3. For samples whose structure is similar to that of the single-crystal samples the changes in the reflection spectra stemming from the transition to the superconducting state are consistent with the BCS theory both in the width of the gap ($2\Delta = 250 \pm 50$ cm^{-1}) and in the behavior of the curves.

4. The penetration of IR light into the test materials reaches a depth of greater than 3000 Å.

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Translated by S. J. Amoretty