Study of the energy gap in superconductors of the Y-Ba-Cu-O system by the IR reflection method

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A procedure is proposed for analyzing the reflection spectra of superconductors to determine the width of the energy gap and to plot its temperature dependence. The value $2\Delta/kT_c$ determined experimentally has been found to be ≈ 3.5.

We have studied the IR reflection from superconducting 1:2:3 ceramics of the composition Y(Eu, Yb)-Ba-Cu-O and also the reflection from a thin film (~ 1 μm thick) grown on a $SrTiO_3$ substrate.

Measurements of the magnetic susceptibility showed that the content of all the samples was that of the superconducting phase (close to 100%). The dc measurements of the conductivity yielded a value $T_c = 94$ K for a $Y_1Ba_2Cu_3O_7$ sample, $T_c = 92$ K for $Yb_1(Eu_1)$ $Ba_2Cu_3O_7$ samples, and $T_c = 91$ K for a thin Y-Ba-Cu-O film with a transition width $\Delta T_c = 1$–2 K for ceramics and $\Delta T_c = 4$ K for a film.

The structure of all the spectra which we have obtained is approximately the same, differing only in the reflection coefficients in the high-frequency region because of the different smoothness of the surface of the samples. The difference spectra, i.e., the plot of the $(R_S - R_N)/R_N$ versus the frequency ν, where R_S is the superconduct-

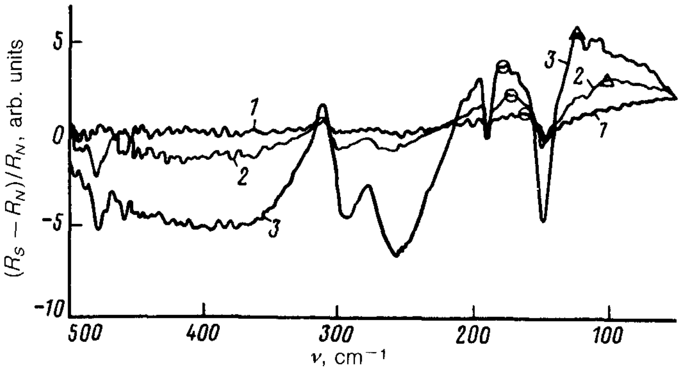

FIG. 1. The dependence $(R_S - R_N)/R_N$ versus the frequency for the ceramic $Y_1Ba_2Cu_3O_7$ with $T_c = 94$ K. Curve 1—R_S was measured at $T = 88$ K; curve 2—R_S was measured at $T = 80$ K; curve 3—R_S was measured at $T = 45$ K. R_N for curves 1, 2, and 3 was measured at $T = 98$ K.

ing-state reflection, and R_N is the normal-state reflection (Fig. 1), which are also similar, contain three bands in which R_S is greater than R_N. These bands are situated in the frequency ranges near 300 cm^{-1}, 180 cm^{-1}, and 100 cm^{-1}. It is clear that the nature of the plot of $(R_S - R_N)/R_N$ versus ν is such that it does not make it possible to single out on it, as was the case with metallic superconductors,[1] a point whose frequency would correspond to the width of the energy gap or to find from its shift at lower frequencies the functional dependence $2\Delta(T)$ as the temperature is raised.

Such spectra were published by Collins *et al.*,[2] and Bonn *et al.*[3] These authors, however, did not present data on the decrease in the width of the gap with increasing temperature up to T_c, and Collins *et al.*,[2] directly suggested that there is no such decrease. These data cast doubt on the existence of the energy gap, since its temperature dependence should lie outside the dependence on the mechanism for the formation of electron pairs, which leads to the formation of such a gap: it should approach zero as T increases to T_c. This dependence has so far been observed in all superconducting metals and alloys as well as in lanthanum ceramics. The temperature-induced shift of the maxima of the difference spectrum can therefore be the test of whether they belong to the energy gap. It can be seen from Fig. 1 (curves 1–3) that the band at 300 cm^{-1} changes with the temperature only in amplitude, while its maximum remains at the constant frequency of 317 cm^{-1}. The maximum of the band at 180 cm^{-1} (marked by a point) shifts, as the temperature is raised, toward lower frequencies by the amount 10–15 cm^{-1}, whereas the maximum of the long-wave band (denoted by a triangle) shifts in the same direction by more than 100 cm^{-1}. We have therefore concluded that the band at 317 cm^{-1}, even though it appears with a transition to the superconducting state, is not directly related to the energy gap, while the other two bands apparently are related to a single gap.

The method we are proposing below allows us to avoid undesirably complicating the difference curve by choosing those spectra for it which were obtained at similar temperatures (differing by only a few degrees).

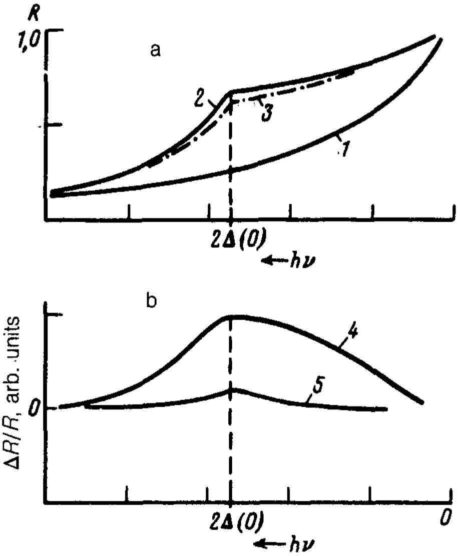

FIG. 2. Idealized reflection spectra of the superconductor for various temperatures. Curve 1—In the normal state at $T_1 > T_c$; curve 2—at $T_2 \approx 0$; curve 3—at $T_3 > T_2$; b—the difference signal $\Delta R/R$ plotted as a function of the frequency; curve 4—$[R(T_2) - R(T_1)]/R(T_1)$; curve 5—$[R(T_2) - R(T_3)]/R(T_3)$, where T_1, T_2, and T_3 are the same as in Fig. 2a.

Let us consider an idealized spectrum of the reflection of a superconductor, which at $T_1 > T_c$ is a quadratic dependence of the wavelength (curve 1 in Fig. 2a). As the temperature is lowered to $T_2 \approx 0$, the material goes superconducting, giving rise to a maximum energy gap for the given material, equal to $2\Delta(0)$ (curve 2 in Fig. 2a). We choose a temperature $T_3 \gtrsim T_2$ in such a way that, on the one hand, the gap width at T_3 will be very close to the gap width at T_2, i.e., $2\Delta(T_3) \approx 2\Delta(T_2)$ (curve 3 in Fig. 2a) and that, on the other hand, the reflection near the gap at T_3 will decrease in comparison with T_2 because of the appearance of auxiliary states which resolve the partial absorption of radiation with an energy[4] $h\nu < 2\Delta(T_3)$. The frequency dependence $[R(T_2) - R(T_3)]/R(T_3)$ will then have a rise with a maximum at a frequency corresponding to the width of the gap at $T_2 \approx T_3$. The error $\delta(\Delta)$ in the value of the gap determined in this manner is given by the relation

$$\delta(\Delta) = 2\Delta(T_2) - 2\Delta(T_3). \tag{1}$$

These qualitative arguments were found to be in good agreement with the results obtained experimentally. In Fig. 3 we see that curve 2, in contrast with curve 1, has only one clearly defined peak at the frequency $\nu = 220\ \text{cm}^{-1}$. We know that at temperatures down to $\sim 0.2T_c$ (Ref. 4) the properties of superconductors in an accurate approximation are in agreement with the properties of the material at zero temperature. We can therefore assume that the width of the gap is $2\Delta(0) = 220\ \text{cm}^{-1}$.

Another choice of the temperatures for the difference spectra: 30–35 K; 50–55 K; 80–82 K, etc. shifts the maximum of these spectra to the frequencies corresponding to the widths of the gap at the given temperatures, allowing the $2\Delta(T)$ curve to be plotted (the inset in Fig. 3).

We can therefore assert on the basis of the results which we have obtained that

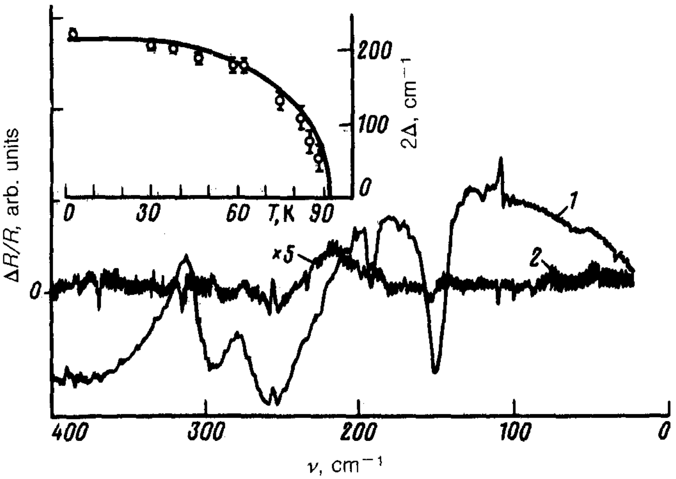

FIG. 3. The difference signal $[R(T_2) - R(T_1)]/R(T_1)$ versus the frequency for the ceramic $Y_1Ba_2Cu_3O_7$ with $T_c = 94$ K. Curve 1—$T_2 = 4$ K, $T_1 = 98$ K; curve 2—$T_2 = 4$ K, $T_1 = 14$ K. Inset—Temperature dependence of the width of the energy gap (solid line—BCS theory; points—experiment).

the materials of the composition Y-Ba-Cu-O have an energy gap with $2\Delta(0)/kT_c \approx 3.5$. The width of the gap depends on the temperature, tending toward zero as T approaches T_c.

Future studies will show whether the agreement of the experimentally obtained characteristics of the energy gap and those derived from the BCS theory is fortuitous or whether this theory describes the superconductivity of a new class of materials.

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