Effect of temperature on the propagation of surface electromagnetic waves in a $YBa_2Cu_3O_{7-\delta}$ film

E. V. Alieva,[1)] G. N. Zhizhin,[1)] L. A. Kuzin,[1)] E. V. Pechen', E. I. Firsov,[1)] and V. A. Yakovlev[1)]

P. N. Lebedev Physical Institute, Academy of Sciences of the USSR
Submitted 14 July 1989
Zh. Eksp. Teor. Fiz. **97**, 566–569 (February 1990)

A plasma frequency of 13 500 cm^{-1} and free carrier collision frequency of 1600 cm^{-1} for a monocrystalline $YBa_2Cu_3O_{7-\delta}$ film are obtained by phase spectroscopy of surface electromagnetic waves, on the assumption of the applicability of the Drude model. The carrier concentration is found to be independent of temperature in the 10 to 300 K range.

Phase spectroscopy of surface electromagnetic waves (SEW)[1] can be used to obtain the optical characteristics of various materials. The propagation of a SEW along the surface of a ceramic and monocrystalline $YBa_2Cu_3O_{7-\delta}$ has been studied only at room temperature.[2,3] By interference measurements, one can obtain the complex dielectric permittivity ε, the plasma frequency ν_p and the free carrier collision frequency ν_τ (on the assumption that the Drude model is valid).

In this paper we study the propagation of a SEW along a monocrystalline $YBa_2Cu_3O_{7-\delta}$ film in which the c axis is oriented perpendicular to the plane of the substrate. The investigation has been carried out in the temperature interval 10–300 K. Both ε and the free-carrier characteristics were determined in a ten-micron range.

A film of 1 μm thickness was grown on a monocrystalline substrate of strontium titanate, oriented in the (100) plane, by the magnetron sputtering method.[4] The superconducting transition temperature in the film was 91 K; the transition width was 0.5 K. The orientation and structure of the film were checked by x-ray diffraction analysis and by the Raman scattering spectrum.

The optical design of the experiment is shown in Fig. 1. CO_2 laser radiation (930–1088 cm^{-1}) is focused on a ~ 10 μm gap between the sample and the screen. After diffraction at the gap, part of the radiation was transformed into a SEW, and part propagated in the form of a diffracted body wave. Having reached the sample edge, the SEW collapsed and was transformed into a second body wave. The body waves interfered with each other, overlapping in the region of angles $\theta \lesssim 50°$. The positions of the extrema of the interference map were determined by the difference in the optical paths of these waves. The optical path of the surface wave depends on the real part of the effective index of refraction of the SEW in the sample, n_e'. The modulation in the interference map is determined by the extinction, on the path a from the screen to the edge of the sample, of the wave propagating along the surface. Extinction is determined by the imaginary part of the effective index of refraction, n_e''. Thus ,having recorded several interferograms for different a, we can determine the effective index of refraction of the SEW:

$$n_e'+in_e''=[\varepsilon/(\varepsilon+1)]^{1/2}. \quad (1)$$

The sample holder allowed the distance a to be changed by translating the screen along the film surface. The MK-30 pyroelectric radiation detector moved along an arc of a circle centered on the exciting aperture. Interferograms are presented in Figs. 2 and 3. The angular positions of the extrema θ_m were determined by the following relationship:

$$1-\cos\theta_m=1-n_e'+(m+\Delta)/2a\nu, \quad (2)$$

where m is the number of the extremum (even for maxima, odd for minima), ν is the radiation frequency, and Δ is an additional phase advance. As is obvious from Eq. (2), the dependence of $1-\cos\theta_m$ on m for different values of a gives a family of straight lines, intersecting at the point $(-\Delta, 1-n_e')$. The slope of the line determines the value of a. The absorption coefficient of the SEW, $\alpha = 4\pi\nu n_e''$, can be determined from the relation

$$\alpha a=2\ln[(I_{\max}^{1/2}+I_{\min}^{1/2})/(I_{\max}^{1/2}-I_{\min}^{1/2})]+A, \quad (3)$$

where $I_{\max}$ and $I_{\min}$ are values of the envelope passing, respectively, through maxima and minima of the interferogram, and A is a constant depending on the efficiency of SEW generation. It is assumed that A and Δ do not change as functions of a; that is, the gap between screen and sample is constant. For temperature measurements the sample was placed on the cold lead of a cryostat with a helium pump. To record the interference map in a large angular interval in the cryostat, a large-sized potassium bromide window was provided. Temperature was varied from 10 to 300 K by varying the rate of helium pumping, and was measured by a copper-constantan thermocouple in the range 20–300 K, or by a silicon diode (10–100 K).

The scheme described above for taking an interferogram at room temperature (see Fig.2) resulted in a value of $n_e'-1=2.54\times10^{-3}$ for the effective index of refraction. Assuming the validity of the Drude model, we can evaluate the free-carrier parameters: $\nu_p = 13\,500 \pm 2000$ cm^{-1}, $\nu_\tau = 1600$ cm^{-1}. This gives a value $\varepsilon = -37+61i$.

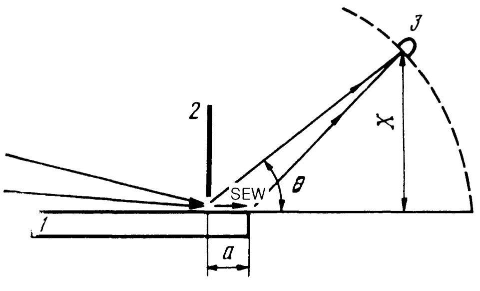

FIG. 1. Experimental design: 1—sample; 2—screen; 3—detector.

 0038-5646/90/020315-02$03.00

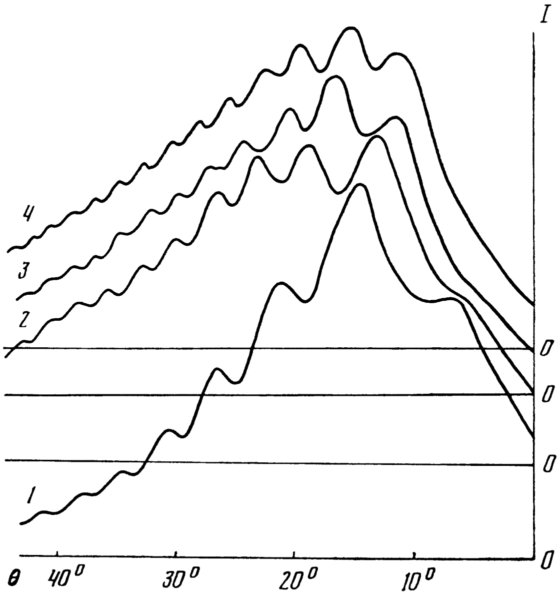

FIG. 2. Interferograms of a $YBa_2Cu_3O_{7-\delta}$ film for different values of a at room temperature: $a = 135\ \mu m$ (1), $175\ \mu m$ (2), $330\ \mu m$ (3), $550\ \mu m$ (4).

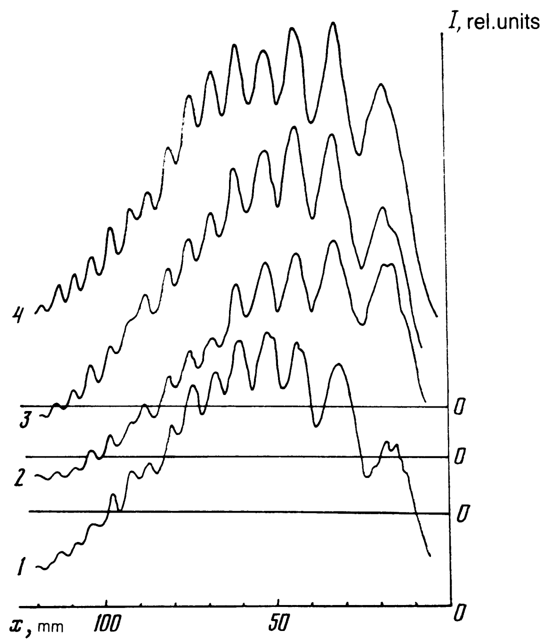

FIG. 3. Interferograms of a film taken at different temperatures (X is the detector displacement): $T = 10$ (1), 100 (2), 155 (3), 290 K (4).

The interferograms shown in Fig. 3 for different temperatures were obtained at $a = 400\ \mu m$. It is not difficult to see that as the temperature varies, the positions of the extrema remain practically unchanged; this proves that ν_p is independent of temperature. Notwithstanding some variation in the form of the curves with temperature, the calculated values of ν_τ also stay constant in the temperature interval 10–300 K within the limits of accuracy of the measurement ($\sim 15\%$). In general, a certain smoothing-out of the temperature dependence of ν_τ can be brought about by the presence of sample surface roughness with a characteristic dimension greater than $1\ \mu m$. However, the surface of the film investigated was mirror-smooth, with a characteristic relief substantially less than $1\ \mu m$.

An important conclusion of the results obtained is the absence of a significant variation in the carrier concentration (more precisely, its relation to the effective mass) in the temperature interval 10–300 K. As is well known, for high-temperature superconductors there is a characteristic decrease in the Hall coefficient R_x, by a factor of 2 or 3, with temperature increase from T_c up to 300 K (see, for instance, Ref. 5, where the measurement of R_x is carried out on identical samples). This behavior of R_x may be due to variation in the carrier concentrations or the presence of sharp singularities in the density of electronic states near the Fermi energy E_F (for example, a narrow d-band of width $\lesssim kT$, where k is the Boltzmann constant). The absence of a temperature dependence in the plasma frequency indicates that the free-carrier concentration does not vary. Therefore, we can propose that the electronic structure of the compound $YBa_2Cu_3O_{7-\delta}$ contains at least one partially filled narrow band of width $\lesssim 100$ K near E_F.

[1)] Institute of Spectroscopy, Academy of Sciences of the USSR.

[1] S. A. Voronov, G. N. Zhizhin, V. I. Silin *et al.*, *Spectral Methods of Solving Problems in Solid State Physics*, Scientific Conference on the Problem of Spectroscopy of Atoms and Molecules (Academy of Sciences of the USSR, Moscow, 1988) p. 202.
[2] G. N. Zhizhin, K. V. Kraĭskaya, L. A. Kuzin *et al.*, Fiz. Tverd. Tel. **30**, 929 (1988) [Sov. Phys.—Solid State Physics **30**, 541 (1988)].
[3] A. F. Goncharov, G. N. Zhizhin, S. A. Kiselev *et al.*, Phys. Lett. A **133**, 163 (1988).
[4] E. V. Pechin', A. V. Varlashkin, A. I. Golovashkin *et al.*, *Physical Chemistry and Technology of High-Temperature Superconducting Materials* (Nauka, Moscow, 1989) p. 350.
[5] A. I. Golovashkin, S. I. Krasnosvobodtsev, I. V. Kucherenko and E. V. Pechen', Pis'ma v Zh. Eksp. Teor. Fiz. **48**, 27 (1988) [JETP Lett. **48**, 27 (1988)].

Translated by I. A. Howard